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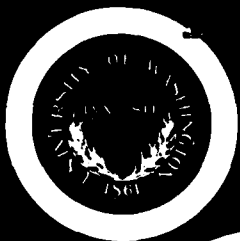
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## INTRODUCTION

A broad program in oceanographic research is carried out at the University by a diverse group of faculty members, professional staff, graduate students, and supporting personnel. The research program is largely in support of our graduate teaching program, so that facilities and projects are available for graduate student research leading to Master's and Doctor's degrees.

Well equipped teaching and research laboratories are augmented by a research fleet consisting of the 209-foot general oceanographic research vessel, the *T. G. Thompson*, two 65-foot research vessels, the *Hoh* and the *Onar*, the 50-foot *Kestrel*, and various small craft. Cooperative arrangements with the National Marine Fisheries, the National Ocean Survey, and the Pacific Marine Environmental Laboratory of NOAA and with the Coast Guard, the U. S. Navy, the Geological Survey, the Corps of Engineers, the Department of Ecology, and other governmental organizations extend our research opportunities.

The research projects range from one-man individual research to participation in multiuniversity, multidisciplinary projects, such as the International Southern Oceans Study (ISOS), the Mid-Ocean Dynamics Experiment (MODE), and the Coastal Upwelling Ecosystems Analysis (CUEA) project, all sponsored by the International Decade of Ocean Exploration (IDOE). Independent research is sponsored by a number of federal, state, and other governmental agencies, including the National Science Foundation, the Office of Naval Research, the Atomic Energy Commission (Energy Research and Development Agency), the Environmental Protection Agency, the Geological Survey, National Oceanic and Atmospheric Administration (NOAA), the Metropolitan Municipality of Seattle (METRO), the U. S. Army Corps of Engineers, and the Washington State Department of Ecology, as well as by private organizations.

The research reported herein is organized by research program elements which define a single or a closely related set of oceanographic questions. These research elements contain, to varying degrees, the fundamental disciplines upon which oceanography is based and range from those which involve a single discipline to those which depend upon all the fundamental disciplines. The faculty, staff, and students associated with each research topic are identified in the body of the report; square brackets indicate the faculty members under whose direction the research is undertaken. Inquiries may be addressed to them or to the Assistant Chairman for Research.

### The Faculty

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- Wearn, Richard B., Jr., Ph.D., Harvard. Physical oceanography, mid-ocean dynamics, ocean pressure fluctuations.
- Welander, Pierre L. R. S., Ph.D., Stockholm. Theory of general ocean circulation, large-scale atmosphere-ocean interaction.
- Whitledge, Terry E., Ph.D., Washington. Chemical oceanography, nutrient regeneration by zooplankton and nekton.
- Winter, Donald F., Ph.D., Harvard. Applied mathematics, hydrodynamics, biological modeling.
- Worsley, Thomas R., Ph.D., Illinois. Stratigraphy, micropaleontology, marine geology, sedimentary processes, paleoecology.

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## SUMMARY OF CURRENT RESEARCH

### I. Dynamics and Thermodynamics of the Upper Ocean

The processes taking place in the upper ocean govern the behavior of the ocean and, to a large extent, of the atmosphere. They play a major role in considerations of climatic fluctuations, a field receiving increased attention at the present time. Research is aimed at explaining the processes involved in the exchanges of properties between the ocean's upper layers and the overlying atmosphere or ice. These exchanges include energy, momentum, heat, water, salt, oxygen, carbon dioxide, and other gases.

#### *A. Ocean-Atmosphere Response Studies*

The Pacific Marine Environmental Laboratory (NOAA) has continued its studies in upper ocean-atmosphere response (OAS) to windfield variations of periods from a few hours to a few weeks. During the summer of 1973, three instrumented buoy systems were deployed concurrently. A shallow-water (70 m) and two deep-water (2750 m) moorings with meteorological and near-surface oceanographic instrumentation were deployed off the Oregon coast; this was part of the Coastal Upwelling Experiment (CUE-2). The deep-water moorings, which were placed close to each other, allowed estimation of horizontal and vertical coherence of inertial waves in the vicinity of the thermocline, their generation and decay by wind stress variations, and thermocline response. Data from this experiment are presently being analyzed.

During March and April 1974, another upwelling experiment (JOINT-I) was conducted off the northwest coast of Africa. Two buoys similar to those described above for the CUE-2 experiment were deployed.

Another experiment, a contribution to the GATE project, was carried out during August 1974 in the tropical Atlantic Ocean. Two buoy systems highly instrumented for near-surface currents, winds, temperatures, radiation, and pressure measurements, as well as for many subsidiary measurements such as line tilt and tension, were deployed. (Halpern)

#### *B. Wind Wave Spectra*

During the winter 1972-73, a submerged pressure gauge was mounted on the summit of Cobb Seamount in the Pacific Ocean. The depth of the sensor was 35 m. The purpose of the experiment was to record winter wave conditions for the Maritime Administration. Seven months of three records per day were obtained. Each record lasted one-half hour with a sample density of .8789 seconds. The tidal constituents have been calculated for Cobb Seamount. Currently this offshore record is being compared with the onshore stations from northern California to Prince Rupert, British Columbia. The data also have provided some interesting aspects to be looked at from a theoretical basis. (Larsen, Irish)

A paper on the wave observations was presented at the International Symposium on ocean wave measurements and analysis in Louisiana, September 1974.

This paper was oriented towards the engineering aspects and the maximum conditions with respect to structures and ships. As the data are unique, we are using the information to improve prediction models for swell. (Larsen)

### *C. Laboratory Studies of Sea Ice*

#### 1. Sea ice melt ponds

We have studied experimentally and theoretically a phenomenon observed in the summer Arctic, where a fresh water layer at a temperature of  $0^{\circ}\text{C}$  floats both over a seawater layer at its freezing point and under an ice layer. Our results show that the ice growth in this system takes place in three phases. First, because the fresh water density decreases upon supercooling, the rapid diffusion of heat relative to salt from the fresh to the salt water causes a density inversion and thereby generates a high Raleigh number convection in the fresh water. In this convection, supercooled water rises to the ice layer where it nucleates into thin vertical interlocking ice crystals. When these crystals grow down to the interface, supercooling ceases. Second, the presence of the vertical ice sheets not only constrains the temperature and salinity to lie on the freezing curve but allows them to diffuse in the vertical. In the interfacial region, the combination of these processes generates a lateral crystal growth, which continues until a horizontal ice sheet forms. Third, because of the  $T$  and  $S$  gradients in the sea water below this ice sheet, the horizontal sheet both migrates upward and increases in thickness. From one-dimensional theoretical models of the first two phases, we find that the heat transfer rates are 5-10 times those calculated for classic thermal diffusion. (Martin, Kauffman)

#### 2. Growth of sea ice

Laboratory experiments on the growth of sea ice in a very thin plastic tank filled with salt water, cooled from above and insulated with thermopane, clearly show the formation and development of brine drainage channels; the thermopane insulation permits the ice interior to be photographed. The "sea water" freezing cell is 0.3 cm thick by 35 cm wide by 50 cm deep. Vertical channels with diameters of 1 to 3 mm and associated smaller feeder channels extend throughout the ice sheet. Close examination of the channels shows that they are much narrower at the ice-water interface than higher up in the ice, so that each channel has a 'neck' at the interface. Further, oscillations occur in the channels, in that brine flows out of the channel followed by a flow of seawater up into the channel. Theoretically, a qualitative theory based on the difference in pressure head between the brine inside the ice and the seawater provides a consistent explanation for the formation of the channels; and the onset of a convective instability explains the existence of the neck. Finally, an analysis based on the presence of the brine channel neck provides an explanation for the observed oscillations. (Eide [Martin])

#### 3. Brine channels; blockage of flow by oil

In an attempt to measure the thermal field associated with the formation of brine channels, thermocouples were mounted inside the freezing cell and their output was recorded on magnetic tape. This information will be used to model the way in which brine channels form. Crude petroleum from both the Alaskan North Slope and the Canadian Arctic was injected under the ice in an attempt to

study the entrainment of petroleum by the brine channels. Preliminary experiments show that the oil blocks the flow in the brine channels. We plan to investigate the effect of this blockage on the physical properties of sea ice. (Niedrauer [Kauffman, Martin])

#### *D. Arctic Mixed Layer Investigations*

During the past five years, measurements of velocity, stress, and density fields have been made in the upper 100 m of the Beaufort Sea under late winter and early spring conditions. This work involves a reasonably complete examination of the mixed layer of the Arctic Ocean. The underside of the ice was carefully examined and mapped by divers. The mean and fluctuating velocity fields were measured using orthogonal triplets of component-sensing current meters and the density field was obtained using a Guildline CTD. A small NOVA computer was employed for collection of data from up to 90 current meters concurrently.

During storms moderately well developed Ekman layers are observed, whereas during meteorologically quiet periods density driven jets are more commonly found in this region. In both periods the mixed layer is stably stratified and downward momentum transport appears to occur through convective events. (Smith)

The velocity-velocity and velocity-density correlations within the turbulent Ekman boundary layer are being explored by solving the linear perturbation equations. Ice topography is neglected but a source of mass at the ice cover is included in the problem formulation and is depicted as brine particles that fall through the layer. The mean velocity, density, and eddy viscosity variations are taken from the field measurements. (Spoonier [Criminale])

## II. Planetary-Scale Oceanic Processes

The research in this element is directed towards explaining the planetary distribution of properties in the ocean and sediment and their variability in space and time and towards understanding the processes responsible for their maintenance.

The ocean with its large capacity and slow deep circulation is an effective integrator of annual and seasonal fluctuations in its inputs. By the same reasoning, however, it probably plays a major role in climatic fluctuations and other long-period phenomena. Relationships between atmospheric conditions and ocean currents, temperature, salinity, and life enable interpretation of sedimentary composition and distribution in terms of past climatic fluctuations. The geochemical cycle depends on these planetary-scale processes and they must be understood in order to predict the large-scale effects that will arise when rates of material inputs are changed.

### *A. Combined Wind and Thermohaline Ocean Circulation*

Solutions have been obtained in a  $\beta$ -plane ocean for the current density distributions resulting from imposed wind stress and buoyancy flux fields. They show the separate contributions to the density field arising from the basic diffusive balance and the superimposed boundary layer and internal advection forcing modifications. An interesting result is that certain observed features in the ocean depend on a balance between two opposing effects so that the observed features are sensitive to changes in one or the other forcing mechanism. (Rattray, Welander)

### *B. Theory of Ocean Circulation*

An analytical quasi-linear circulation model has been developed describing the three-dimensional circulation forced by wind and thermohaline surface processes in a rectangular  $\beta$ -plane ocean. The main new result is the demonstration of the effects on the interior mass field by the boundary layers: the top Ekman layer, the side layer ("Gulf Stream"), and the baroclinic up- and downwelling layers. The model can reproduce the observed main thermocline reasonably well.

Continued work on the same circulation model will be carried out by a numerical method, using computers. This will allow a proper treatment of the nonlinear advection of heat and salt. The main purpose is to achieve a complete understanding of the problem as depending on such parameters as the vertical mixing coefficient and the ratio of wind forcing to thermohaline forcing. Such an understanding is missing in studies of the same problem carried out elsewhere.

The study of the large-scale oceanic eddies and their role in the main oceanic circulation has continued. The work has been concentrated on the simplest case: baroclinic  $f$ -plane eddies. Analytical similarity solutions for the three-dimensional time-development of such eddy fields have been found, and are being used to develop an improved mixing-length theory. The next step will include baroclinically unstable  $\beta$ -plane eddies. The most unstable eddies will be allowed to feed back to the mean current, thereby closing the circulation problem -- a line already successfully tried by other investigators for the

general atmospheric circulation. This work involves analytical as well as numerical modeling. Results will be tested against data from the Atlantic MODE-experiment and anticipated data on eddies from the Pacific. (Liu [Welander, Rattray])

#### *C. Dynamics of the Southern Ocean*

The International Southern Ocean Studies (ISOS) is a program of dynamics and monitoring experiments in the Southern Ocean aimed toward the understanding of the long-term, large-scale variability of dynamical processes and the interaction of the Southern Ocean with the global circulation. The project is supported by IDOE and is jointly managed by the University of Washington and four other institutions. A field program, carried out by the Department of Oceanography and the Applied Physics Laboratory, University of Washington and the New Zealand Oceanographic Institute, to monitor the northward flow of Antarctic Bottom Water in the western boundary current along the coast of New Zealand will begin in 1975. Understanding of the variability of this flow is crucial to the global circulation because it links oceanic processes in the Southern Ocean to the rest of the World Ocean. In this role, the flow may play a major part in long-term climate dynamics. (Baker, Taft, Wearn)

#### *D. Abyssal Processes in the North Pacific*

A study of the abyssal currents in the North Pacific was begun in 1973. An array of current meters was deployed in the North Pacific north of Hawaii to obtain time series of velocity. The array will be maintained for at least two years to obtain estimates of the low-frequency fluctuations of current velocity. The distributions of temperature, salinity, dissolved oxygen, and nutrients in the deep water of the North Pacific will be used to infer the large-scale flow. Tracer studies will be incorporated in order to assess the diffusion characteristics at abyssal depths. (Taft, Ewart)

### III. Meso-Scale Oceanic Processes

Studies on meso-scale processes seek to explain those oceanic features which are embedded in the planetary-scale phenomena but have an identifiable existence of their own. These include frontal patterns, eddy structures, domes, and oceanic upwelling areas; distributions of unusual properties; and topographically induced flow patterns. They typically can respond with periods from days to years. They can be associated with weather patterns, and biologically productive and unproductive regions. They may have a large influence on the planetary-scale motions and in turn be modified or caused by these motions.

#### A. Offshore Tides

The behavior of the tides in the deep ocean is still not completely known. One of the difficulties with analysis of the spatial behavior of tides is that they are strongly dissipative near river mouths and harbor entrances, where the majority of the coastal tide gauges are located. Several tidal records offshore on the continental shelf off the Columbia River, on the continental slope off Vancouver Island, and 500 km seaward on Cobb Seamount have been obtained; they will be used to study the behavior of the tides in the Northeast Pacific. Besides global modeling, simplified theories and observations have been combined to predict the behavior of offshore tides. The solution to this problem will provide aid to the theoretical and experimental work on the generation of internal tides since we would then have a good idea of the tidal currents over the shelf break and slope which generate internal tides. (Irish, Larsen)

#### B. Internal Tides

Field experiments have been conducted on the continental slope off Vancouver Island in an attempt to measure the structure of the seaward propagating internal tide beam. Temperatures from thermistors attached to moored arrays at fixed depths in the beam were measured for greater than 1 lunar month. Deployments of these arrays were made in 1969, 1970, and 1973. So far the data return has been minimal and the record lengths less than optimal; therefore, an accurate determination of amplitude and phase across the beam is impossible. However, in the portion of the beam studied, an upward propagation of energy was found; but this section does not correspond with the maximum energy peak at the lower edge of the beam. Analysis of some STD records taken at the site over a 5-day period yields a peak in amplitude of about 1 km depth. The phase appears to propagate upward across this peak but to propagate downward above the peak as indicated by the temperature series at these depths. An experiment carried out in summer 1973 measured temperature at many depths across the beam. The results were similar to those obtained in 1970 but with some important differences in the phase relations. (Irish, Larsen, Rattray, Dworski; Barbee, NOAA)

Theoretical studies on the mechanism for the generation of internal tides by bathymetric coupling with the surface-tide, particularly over the continental shelf and slope, are continuing. The internal tide beam bends downward as it moves seaward away from the shelf break with intensification of the vertical particle displacements at the lower edge of the beam relative to the rest of the beam. Friction causes the oceanic beam to widen as it progresses seaward and destroys any of the fine structures caused by coupling between the shelf and oceanic internal waves. The slope also generates internal waves which modify the beam that is generated at the shelf break. Laboratory experiments verify qualitatively the theoretical results. (Prinsenbergh [Martin, Rattray, Hachmeister])

### C. Deep-Sea Instrumentation and the Mid-Ocean Dynamics Experiment

Data collected from four quartz crystal bottom temperature gauges in the MODE-I experiment (March-July 1973 in the Sargasso Sea) are currently being analyzed. The instruments were mounted 1 meter above the bottom (5400 m) at the vertices of an equilateral triangle 200 km on a side. The temperature showed large fluctuations (.03 to .05°C) over periods of one to two weeks and strong coherence at 1 km horizontal spacing. The coherence at 200 km was weak. One abrupt temperature drop of 0.12°C over 50 hours was observed at the western site; we estimate a velocity of propagation for this "cold front" of about 5 cm/s and a horizontal gradient of about 0.01°/km. The presence of this front and other large temperature fluctuations may be associated with Antarctic Bottom Water as shown by the salinity and temperature structure near the bottom in this area.

Our quartz bourdon tube deep sea pressure gauges, which yielded the first long (91 days) deep-sea pressure record from the MODE-I area, are currently undergoing a series of drift and reliability tests. They are exceptionally stable and sensitive instruments and if they pass these stringent tests, will be used for the transport monitoring of major ocean currents. (Baker, Wearn)

### D. Central Arctic Ocean

#### 1. Baroclinic features

This continuing program emphasizes direct current measurements and water-mass analysis to elucidate the fluxes of mass and energy through the ocean. We have now completed the analysis of the 1970-72 AIDJEX Pilot Study data. Among the most important results are:

- 1) The identification in the Canadian Basin of wave-like baroclinic features with crests oriented perpendicular to the mean flow and wave lengths of 100-200 km. These features appear to be Rossby waves of period 16-32 weeks. Isopycnal displacements associated with these waves are of the second mode, resulting in nearly geostrophically balanced current maxima 2-8 cm sec<sup>-1</sup>) in the pycnocline.
- 2) The identification of baroclinic eddies as the source of high-speed currents (30-50 cm sec<sup>-1</sup>) observed in the pycnocline. Most of these eddies appear to be anticyclonic. A typical eddy (Figure 1) has a central core with radius about 6 km, which is in solid-body rotation. This core is surrounded by a region of large vorticity gradient. At radii greater than about 8 km the motion is nearly irrotational, although the eddy noticeably influences the velocity field out to about 15 km from the center. Such eddies are apparent in 1/3 to 1/2 of the available current records and, hence, represent a fairly common feature. T-S correlations show the eddies to have water different from ambient, implying that the eddies are not locally generated.

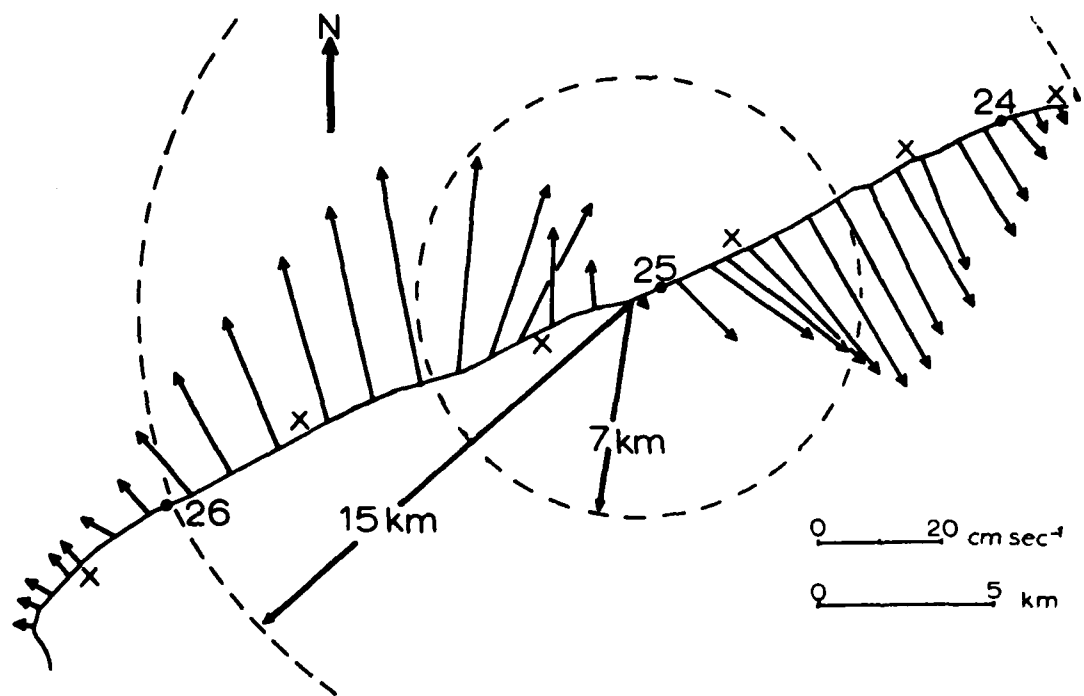


Figure 1. A baroclinic eddy in the Arctic Ocean

Two-hour averages of true 150 m currents (center of pycnocline) during AIdjex Pilot Study, March-April 1972. Ice station drift 24-26 March is solid line, and hydrographic stations were taken at positions marked X. The dashed circles show the extent of the eddy's influence and approximate radius of maximum velocity.

## 2. Beaufort Gyre

The nature of the Beaufort Gyre has been reexamined. This circulation is maintained by the wind stress pattern as modified by the ice cover, but in the shallower areas near the coasts and within the Chukchi Province it is strongly affected by the bottom topography. The mean flow of the Atlantic Water (centered at 500 m) is also anticyclonic within the deep basin; however, there is evidence for a subsurface countercurrent along the Chukchi Rise. This flow apparently is a continuation of Atlantic Water entering from the west directly across the deeper southern portions of the Chukchi Province. (Newton [Coachman, Aagaard])

## 3. Currents and hydrography: ice island T-3

A new program of continuous current measurements at fixed depths beneath ice island T-3, wherein the recording instruments were replaced on a regular basis, obtained 9 months of records. Station drift was determined from satellite navigation. The program also included detailed and frequent hydrographic work with bottle casts and CTD profiling. An objective of the latter effort was to statistically determine some effects of the annual convective cycle. (Hanzlick [Aagaard, Tripp])

## E. *Greenland Sea*

### 1. Deep and Bottom waters

A volumetric analysis of the Greenland Sea Deep and Bottom waters indicated a seasonal variation in the Deep Water volume of  $30 \times 10^3 \text{ km}^3$ , corresponding to an outflow rate of  $3 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$  during summer. Winter data indicated that Bottom Water is not formed at the sea surface, but rather by a subsurface modification of Atlantic Water within the Greenland Gyre. The formation mechanism appears to involve two separate large-scale convective regimes coupled by a double-diffusive process in which the effective turbulent diffusion coefficient for heat is about three times that for salt. (Aagaard)

### 2. Time-dependent aspects of currents

Considerable progress has been made in the analysis of drogue measurements in the Greenland Sea and of year-long moored current measurements in the Greenland-Spitzbergen passage. The work has concentrated on the time-dependent aspects of the currents, including tidal modes and periodicities probably related to planetary waves, and on transports of mass and heat. Among important new results are mass and heat budgets for the Arctic Ocean which show over one half order of magnitude more heat being advected into the Arctic Ocean than previously thought. This has particularly important consequences for the vertical heat fluxes and climatology of the Eurasian Basin of the Arctic Ocean. (Aagaard, Coachman)

## F. *Iceland Sea*

In cooperation with the Marine Research Institute in Reykjavik, Iceland and with ship support from the U. S. Coast Guard, we have begun a new project in the Iceland Sea. A series of occupations of a tight station grid using STD's will provide data for volumetric and other analyses to elucidate the seasonal

climatological processes. Additionally, the transmittal and modification of Deep Water in the Iceland Sea, as well as the role of Polar Water from the East Greenland Current in the occurrence in recent years of the anomalously extensive ice distributions, will be studied. Cruises in August and October 1974 have been completed. (Swift [Coachman, Aagaard])

#### *G. Bering Sea*

##### 1. Water masses of the deep basins

A comprehensive survey, during a fall season, of the central and western deep basins was successfully completed during October-November 1973. The data provide a substantial base for volumetric T-S analyses of the water mass distributions and interactions, now under way. For the first time, assessment of seasonal change will be possible as most earlier data were from summer. (Aagaard, Coachman)

##### 2. Currents

Emphasis of the current studies has shifted to the eastern Bering Sea, where exchanges between the deep basin and the extensive eastern Bering Sea shelf are the primary focus of the research. The summer 1972 cruise of the *Thompson* was a quasi-synoptic survey of the continental slope where a current from southeast to northwest was thought to exist. The data define a current (Bering Slope Current) composed of three filaments: two northwest-bound streams, each transporting 2-4 Sv, one over the continental slope and the other well offshore, and a southeast flow between, of similar magnitude. The current is not well defined by the dynamic topography, however, which rather shows a pattern of highs and lows. A coherent explanation involving incoming and reflected baroclinic Rossby waves of about one-year period, generated in the region of maximum wind torque over the central Aleutians, is possible. (Coachman, Galt)

##### 3. Upwelling and shelf-deep basin exchange

Other studies are under way on data from Zhemchug Canyon, located midway along the shelf, and the region north of Smalaga Pass; both areas show evidence of extensive upwelling. An intensive study over Pribilof Canyon, also believed to play an important role in shelf-deep basin exchange, was made in July 1974 in cooperation with scientists from the Faculty of Fisheries, Hokkaido University. (Coachman, Tripp)

##### 4. Resource potential of the shelf

A comprehensive research study of the Bering Sea (Processes and Resources Of the Bering Sea Shelf: PROBES), which will ultimately become international (Japan, USSR), is being planned. This study will be of the magnitude which is required if we are to ever realize and rationally utilize the enormous resource potential of this sea. (Swift [Aagaard, Coachman, Galt])

#### *H. Fronts and Transition Zones of the Central Pacific*

Three oceanic fronts are encountered in the North Pacific. The *subarctic front* occurs between latitudes 40-42°N and is characterized by strong horizontal temperature and salinity gradients, which balance each other in such a way that

the resulting horizontal density gradients are small. This front is most pronounced in the upper 100-150 m.

The *subtropical front* which is found between latitudes 30-32°N is prominent in the upper 100 m. In winter and spring, both the horizontal temperature and salinity gradients are strong, but in summer and fall only the salinity gradients are large.

The *doldrum front* occurs between latitudes 9-11°N and is most pronounced in the upper 50 m. It is characterized by strong, horizontal salinity gradients, which are not balanced by corresponding horizontal temperature gradients in the upper layers. Because of this imbalance, strong baroclinic flow is encountered near this front.

During the past years, significant progress has been made in understanding processes that lead to the formation and maintenance of oceanic fronts. It has been determined that fronts will develop and intensify in those regions where areas of heat and salt gain are in close proximity to each other and where there is a convergent flow pattern of currents of different origin. Depending upon the relative magnitude of the factors affecting oceanic frontogenesis, temperature and salinity fronts may coincide, or be displaced relative to each other; in some cases multiple fronts will develop. Strong baroclinic flow is encountered only at those fronts where an imbalance in the density gradient exists between the horizontal temperature and salinity gradients.

The frontal zones are marked by a complicated vertical thermohaline structure. Numerous temperature and salinity inversions are found and there is usually an abrupt change in the characteristics of the high stability layer from one side of the front to the other. At the subarctic front, the deep sound channel surfaces during the colder part of the year. During January and February 1974, an intensive field study was made of the subtropical front north of Hawaii. The object was to study the thermohaline structure of the front and its variation in space. The relationship of the front to the atmospheric and oceanic flow fields and to the energy exchange through the sea-air interface also is being investigated. (Roden)

### *I. Kuroshio Studies*

In 1971 and 1973 cruises were made south of Japan to study the characteristics of the Kuroshio flow. Determinations of the path of the current by means of temperature soundings have shown that there are regions of rapid fluctuations and also other regions where the current path is very stable in time. Comparison of the movements of the current with bottom-current measurements have indicated that movements of the current east of Cape Shionomisaki can be related to the near-bottom velocity measurements in a simple way. This suggests that, at least over the portion of its path, the Kuroshio reaches to the bottom.

The behavior of the current as it flows across the Izu-Ogasawara Ridge was studied by making current velocity measurements along the axis of the ridge and hydrographic and OBT casts across the ridge. The current measurements indicated the regions where the deeper water in the Kuroshio crossed the ridge and the effect of the ridge on the horizontal density structure was described. The Kuroshio near the surface appears to broaden and weaken on the ridge, and then intensify downstream from the ridge. Interpretation of the nature of the interaction of the current with the ridge is being made, using models that conserve potential vorticity. (Taft; A. R. Robinson, Harvard University)

As a part of the North Pacific Experiment (NORPAX), a field program is being carried out with the cooperation of the Institute of Oceanography of the National Taiwan University. Hydrographic stations and surface current measurements will be made across the Kuroshio six times within a year. The computed geostrophic transport will be compared with differences in sea level recorded at tide-gauge stations on Taiwan and on Ishigakijima Island in the Ryukyu Chain. The usefulness of the sea-level fluctuations as an index of transport fluctuations will be assessed. (Taft)

*J. Saronikos Gulf*

Extensive oceanographic data, from eleven cruises over a period of 18 months, have been collected from Saronikos Gulf, Greece. Hourly wind measurements and daily measurements of other meteorological parameters are available for the period. Analyses of the circulation patterns and their relationship to the wind field have been started. Concurrently, two numerical models of the circulation are under development. Both use similar physics (basically Ekman and barotropic modes) and include bathymetry, but solution of the equations is obtained through very different techniques. This study will provide not only knowledge of the circulation in Saronikos Gulf, which will aid in solving major pollution problems, but also comprehensive testing of the validity and usefulness of various numerical modeling techniques on a meso-scale wind driven system. (Coachman, Galt, Lee)

#### IV. Small-Scale Physical Processes

The purpose of research in small-scale physical processes is to improve understanding of turbulence, short internal waves, microstructure, layering, and sound transmission and their interactions in a stratified, geophysical shear flow. These processes provide the mechanism for nonadvective fluxes important to maintaining oceanic distributions. In addition, their presence causes a severe sampling problem in determining the large-scale, more slowly varying, state.

##### *A. Mixing and Turbulence in Stratified Fluids*

Density and velocity distributions between two moving streams have been determined theoretically and the results are in agreement with Lofquist's measurements for fresh and saline water in relative motion.

Various instability modes of a density interface, namely Miles shear instability, Richardson instability, and Kelvin-Helmholtz instability, are being considered. Their physical implications in relation to salt-wedge stability will be studied. (Lee)

A field investigation of mixing in stratified fluids is being carried out to determine how seawater and river water are mixed together in various types of estuaries. The results, of course, are equally applicable to the pycnoclines in the North Pacific and Arctic oceans, but phenomena such as this are best studied on a natural scale in an area such as Puget Sound where some control over the experiment is permitted. (Smith)

A linear perturbation technique is being employed to analyze the resulting unsteady motion that ensues after the introduction of particular initial disturbances onto a mean equilibrium, characterized by velocity and density profiles that can be expected in an estuary. Numerical techniques are combined with analytical approximations for the mean variations with depth to produce quantitative results. Of salient interest is the fate of a specified density change at a certain depth to the mean system. (Bradt [Criminale])

##### *B. Turbulent Boundary Layer over Wavy Topography*

The adjustments that occur in the turbulent boundary layer as it flows over topography are being investigated. These adjustments can best be examined when they are caused by regular disturbances, such as sand waves under steady flood conditions in the Columbia River. Therefore, during the past several years detailed measurements of mean velocity and Reynolds Stress fields over these sand waves have been made. The data indicate that the turbulent levels over such a wave field are surprisingly high and that the intensity of turbulence is reasonably uniform downstream. On the other hand, the Reynolds Stress component formed from the downstream and vertical velocity components shows substantial spatial structure. The mean flow over sand waves, where the flow has separated and also where separation has not occurred, has been examined in detail. Even in the latter case a second order theory appears to be essential. Earlier theories are now being revised to make them more consistent with the measured mean velocity and turbulence fields.

Flow behavior over wavy topography has been studied also on the basis of a perturbation expansion procedure. The perturbed turbulent stresses are related to the perturbation strain rate in terms of an eddy viscosity coefficient. With a symmetrical wavy topography, two nonlinear effects, namely the generation of higher harmonics disturbances and the mean flow modification, are considered. It is shown that an asymmetry of the boundary shear stress is a result of such nonlinearity. With an asymmetric wavy topography, the nonlinearity results in super- and subharmonic disturbances and the mean flow modification by the self-interacting harmonics. A physical explanation is proposed for the formation of sand waves under flowing water. Comparisons will be made with flow measurements carried out in the Columbia River. (Smith, Lee)

#### *C. Sublayer for a Turbulent Ekman Boundary Layer*

A theory for the molecular sublayer for a turbulent Ekman boundary layer is being developed along the outline given by J. Sternberg (1962, 1965) for classic flat plate boundary layer without Colioliis effects. (Quinlan [Criminale])

#### *D. Deep Ocean Mixing and Oceanic Microstructure*

Vertical and horizontal diffusion characteristics of the deep ocean below the main thermocline in the vicinity of the Mendelssohn Seamount north of Hawaii was successfully measured in 1972 by the Ocean Physics Group, Applied Physics Laboratory. During the following year, a second and even more successful cruise was conducted west of Baja California beyond the continental shelf. New sensors for the SPURV unmanned submersible platform were designed for this field program and an active isopycnal float was developed and deployed to tag the location of deep dye releases for diffusion measurements. Scientists of the Scripps Institution of Oceanography rendezvoused with our group at sea to collect data with other specialized equipment which they operated. The picture of ocean microstructure which is evolving from our research differs greatly from the models that were hypothesized only a few years ago. In the past the vertical profile of temperature and salinity was deemed to be reasonably smooth, but advances in measurement techniques have now shown that the profile is highly stratified with regions of low and high gradients of temperature and salinity. Layers, a few meters thick, that are nearly isothermal and isohaline, persist for horizontal distances of a kilometer or more. Sharp gradient features (thermal sheets) a few tenths of a meter thick also persist in the horizontal direction for hundreds of meters. These sharp gradient regions can be shown to significantly affect sound transmission. Under certain conditions these layers and sheets can cause acoustic frequency-dependent multipaths and local shadow zones.

A program to take measurements of subcentimeter-scale fluctuations of temperature and salinity from an instrument freely falling through the ocean has been started. This field, known as oceanic microstructure, deals with the smallest-scale fluctuations of importance in the ocean -- the ones responsible for breaking down or dissipating the discrete chemical and energetic exchanges which constantly occur at the sea surface due to interactions with the atmosphere. The interplay which is expected to develop between this work and other ongoing programs should produce some significant advances in understanding the physics of the sea. (Ewart, Gregg)

### *E. Wake Studies*

This year the Ocean Physics Group, Applied Physics Laboratory, initiated a new program to study the characteristics of submarine wakes. The work involves detailed measurement of submarine wake turbulence together with a quantification of background oceanic conditions. The measurements will then be compared with theoretical predictions in order to develop an accurate understanding of the process of wake signature generation. As a secondary benefit from the work, the background data will become an invaluable addition to our knowledge of stratification and internal waves in the thermocline region. We are designing and constructing a new SPURV, designated SPURV II, to carry out this experiment. The new vehicle will have enhanced performance characteristics and a new instrument suite capable of resolving oceanic variables down to subcentimeter scales. Initial field work for this experiment will be carried out in April 1975. (Ewart)

## V. Coastal Dynamics, Upwelling, and Downwelling

The coastal regions have interesting and important properties distinct from the open ocean, both because they act as lateral boundaries and because they are much shallower. The purpose of this program is: to understand the currents and mixing processes and their dependence on the local driving forces and on the conditions in the adjacent ocean; to determine the rates of upwelling or downwelling and their effect on nutrient replenishment and the resulting biological production; the transport processes of sediment over and across the continental shelf; and the chemical reactions that occur as river water enters the sea.

### A. *Field Studies of Coastal Dynamics*

#### 1. Washington-Oregon

Direct current measurements on the continental shelf off Washington were made from 1971 to 1974 at two stations, one on the central shelf and one at the shelf break. Six current meters were usually deployed at each station. Density sections were taken upon deployment and retrieval of moorings. Wind speed and direction were measured at one station, Westport. These data are currently undergoing intensive analyses. Parameters such as velocity shear, response of both components of velocity to wind, volume transport, and the response of the density field to the wind and to the Columbia River influx are being investigated as a function of season and of longshore position. Comparisons between these data and those detailed by Oregon State University off the Oregon shelf have been initiated. In addition, the models of Pietrafesa and Rattray and of Hamilton will be applied to existing data.

Although current measurements have been made on the continental shelf off Washington in all seasons, our primary emphasis is on autumn and winter during which severe storms drive strong north-north-westerly currents along the shelf. Of particular interest is the fact that significant sediment transport occurs only under the influence of the most severe of these storms; during these periods a substantial amount of sediment is transported from the mouth of the Columbia River to the continental slope north-northwest of the river mouth. Another salient feature of the currents over the Washington continental shelf is a reversal of direction with a period, ranging from 3 to 5 days, which appears to be associated with movement of storms across the northeast Pacific Ocean. Such reversals are not entirely unexpected during winter: however, they are found in the currents below 50 m throughout the summer as well. Tidal currents on the Washington continental shelf are also under examination.

Future work includes a longshore winter shelf experiment in January - February 1975. Four moorings will be deployed along the Washington-Oregon shelf; wind will be measured *in situ* at one mooring, as well as on the Columbia River Lightship and at Westport. In conjunction with this experiment, Oregon State University will deploy 3 moorings. Hydrographic sections will be run continuously for six weeks. The objects of the experiment are to investigate (1) longshore variations in currents, wind, sea level, density, and topography; (2) the relationship between density, wind, and current fields in the winter season; and (3) the effect of shelf waves.

In connection with this project, a current meter system to be used in a taut wire mooring but capable of measuring three orthogonal components of the velocity field at frequencies of up to 5 hz is being designed. After a period of field testing, this device will be used to examine the turbulent structure of the upper ocean, to investigate the interaction between wind waves and wind driven surface currents, and to make measurements on the inner part of the continental shelf. (Hickey, Smith)

## 2. West coast of Florida

The pressure gauge and recording package that was used on Cobb Seamount has also been used in connection with a shelf dynamics program on the west coast of Florida. A four-month tide record, with a two-hour sample period, on the Florida shelf was collected in 1973. This record along with eight months of data taken from 18 current meters and another pressure gauge are under study in order to isolate the influence of the loop current in the shelf circulation. (Larsen)

### *B. Theory of Coastal Currents and Upwelling*

A study that shows the response of a rotating stratified coastal region, including both horizontal and vertical density gradients, to various driving mechanisms has been completed. The coupled system of nonlinear equations is solved numerically and analytically using separation transformations for various topographies. The results show upwelling and currents which compare favorably to observations in coastal regions.

A numerical study of the time-dependent circulation on the continental shelf is in progress. The purpose is to study the depth-dependent wind-driven circulation and density distributions in a section normal to the coast, assuming longshore uniformity. The results will be compared with observed upwelling events. (Pietrafesa [Hamilton, Rattray])

## VI. Estuarine Processes

Research in this element is directed toward understanding the processes occurring in these semienclosed bodies where the seawater is appreciably diluted by mixing with the inflowing river water. These processes are unique by virtue of strong gravitational convection, strong tidal currents, and/or large net flows due to river inflows. Such areas are high in biological productivity and for this and other reasons important to man. Quantifying the processes governing the system is scientifically interesting and practically very important.

### *A. Near-Surface Circulation in Fjords*

It is characteristic of fjord flow that the most vigorous circulation takes place in a brackish water zone near the surface. In fjords with appreciable fresh-water input, the flow is generally characterized by one or two reversals in horizontal current direction. The surfaces of no mean motion define the boundaries of two or three circulation zones whose structures change in response to changes in wind and run-off intensity. When most of the fresh water comes from river discharge near the head of the inlet, in the absence of winds, the circulation tends to a two-zone system in which the uppermost zone moves persistently seaward above a landward-moving deeper zone of saltier water. The salinity of the uppermost zone tends to increase in the direction of the mean current due to entrainment of denser, more saline water from the zone below.

One of our primary objectives is the development of an approximate analytical representation of gravitational convection and density structure in the near-surface flow regime. The utility of similarity techniques has been explored in the hope that relatively simple description would emerge for the quasi-steady, nontidal component of fjord circulation. We have made progress with a similarity analysis based on the use of exponential functions of the longitudinal coordinate of the fjord. Approximate solutions for the velocity field and density distribution have been obtained and the results applied to near-surface zones, i.e., above sill depth, of segments of Hood Canal (Figure 2) and the central basin of Puget Sound.

An important shortcoming in the above models arises from inadequate knowledge of the turbulent exchange processes acting in these highly stratified surface layers. Complementary to direct observations of turbulence in stratified fluids, we are investigating the applicability to data obtained under a variety of fjord flow conditions of various functional relationships for eddy coefficients in terms of the density and velocity profiles which control the turbulent processes. An improved representation for these coefficients will enable significantly better theoretical models of the near-surface circulation in fjords. (Winter, Rattray)

### *B. Circulation and Exchange Rates in Puget Sound*

Historical data on water properties and currents, hydraulic model studies, and anticipated high-frequency current and hydrographic samples will be synthesized into a program to better understand basic circulation patterns and exchange rates in Puget Sound. Hydrographic data from 1932 to the present time are available for a large number of locations in Puget Sound and the Strait of Juan de Fuca. The historical data contain information concerning the long-term and

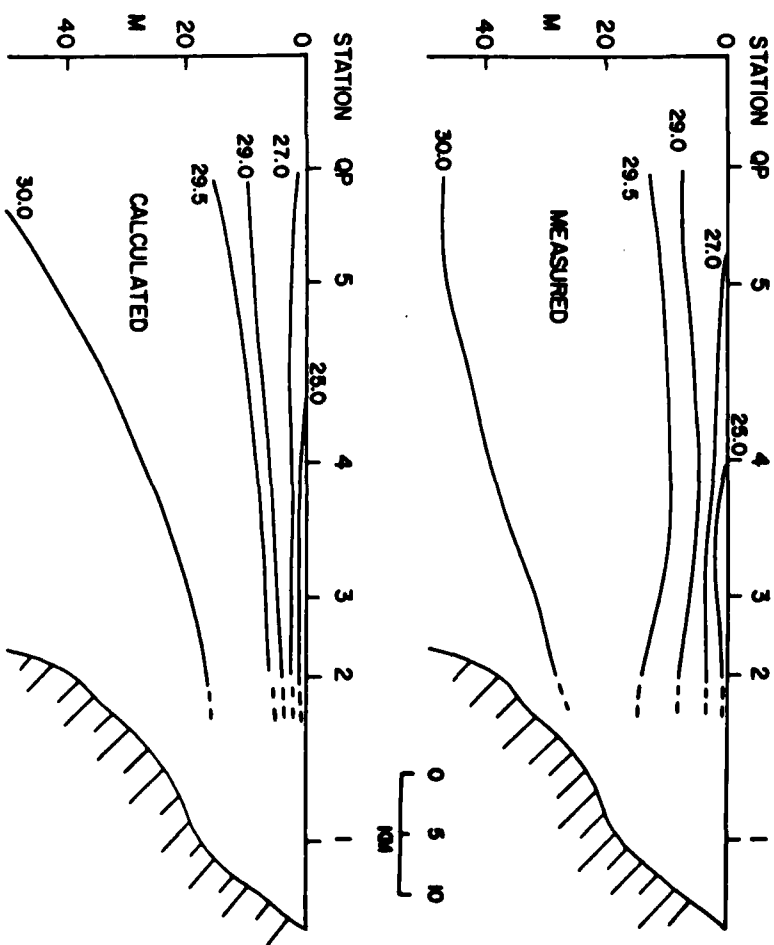
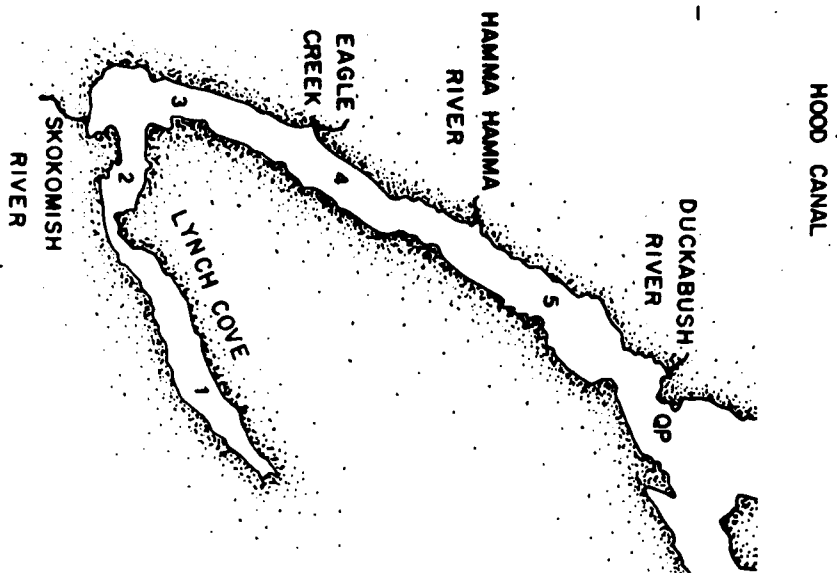


Figure 2. Comparison of measured and calculated salinity distributions in Hood Canal.

seasonal variations in water properties, as well as information pertinent to the average exchange times in the deep waters. However, it is necessary to know the short-term changes in hydrographic properties in order to interpret realistically these data which were mainly obtained at monthly or longer intervals. Use of a hydraulic model of Puget Sound has made it possible to identify areas where additional high-frequency samples are needed. Proposed measurements, in addition to supporting the historical data, are also expected to contribute information concerning the energy associated with motions at different time scales and leading to an understanding of the spatial correlation of physical properties. Ultimately, these studies should provide a sufficient understanding of the physical properties of Puget Sound so that it will be possible to design realistic sampling programs to test various hypotheses concerning fjord circulation. (Lam)

A program initiated by the Pacific Marine Environmental Laboratory (NOAA) in 1972 to investigate the dynamics of Puget Sound was continued during January and February 1973. Current observations and water-property measurements were made from a surface and subsurface mooring in the central basin of Puget Sound ( $47^{\circ}42'N$ ,  $122^{\circ}27'W$ ) for approximately 37 days. Additional water-property measurements were made along and across Puget Sound with the STD. The data are being analyzed to determine the net long-term circulation and mixing characteristics throughout the water column. (Galt)

#### *C. Circulation and Exchange Rates across Entrance Sills*

The circulation and water and salt exchanges across major entrance sills are being investigated in several interrelated studies.

A cooperative investigation with the Department of Environment, Canada took advantage of their extensive current-meter coverage in a cross section of the Strait of Juan de Fuca to jointly run longitudinal and lateral density profiles over a number of tidal cycles. The data are being analysed to determine the dynamic and salt balances under the given external conditions. (Dworski, Rattray)

The importance of the tidal motion in the horizontal diffusion of salt for tidal estuaries is well recognized; however, there are no theories that adequately relate the salt flux to the tide. Preliminary calculations suggest that in certain cases a significant contribution to this salt flux can occur in the bottom boundary layer, but that the actual transport will depend critically on the nature of the boundary layer. This phenomenon is being investigated by combining the theoretical prediction with an experimental program to both guide and validate the theory. A preliminary joint experiment was carried out in the Strait of Juan de Fuca, in cooperation with the Pacific Marine Environmental Laboratory (NOAA), in which both velocity and salinity profiles were measured at a high sampling rate over an interval of 3.6 days. Analysis and interpretation of the data are presently under way. (Dworski, Galt, Hamilton, Irish, Larsen, Rattray)

Hydrographic surveys were conducted along and across Rosario Strait during February and March 1974, in cooperation with the National Ocean Survey. Included were two 25-hour time-series at the north and south ends of the Strait. During these months 17 current-meter stations were occupied for 15 days each, and one

station for the entire period. Lagrangian current measurements were also made by tracking groups of drogues. In addition, 18 tide gauges were installed for 30 days each. The data are being processed and a detailed study is being made of the dynamic balance for the circulation. (Galt)

#### *D. Salt Wedge Estuaries*

A theoretical study giving the circulation and salt wedge configuration in a class IV estuary has been completed for a model estuary of rectangular cross section with a constant bottom slope. Comparison between theory and observation is favorable for the Mississippi and Duwamish Rivers.

An experimental program is being initiated to measure the turbulent salt flux in the Duwamish River under a number of flow conditions ranging from a salt wedge to a moderately mixed estuary. The observed conditions for salt wedge breakdown will be compared with the theoretical studies. (Mitsuda [Rattray])

#### *E. Density Fronts and Patches*

Color-infrared vertical aerial photography was used to locate lines of convergence at density/turbidity discontinuities in Rosario Strait and North Skagit Bay. Transmissometer profiles of such a front between low density water trapped by the fixed boundaries of North Skagit-Similk Bay and the tidal flood through Deception Pass showed a subsurface extension of the surface convergence line, dipping at an angle of approximately  $45^\circ$  beneath the lower density mass.

Time-series STD and suspended sediment concentration measurements were made in Rosario Strait for a two-day period in April 1974. This experiment was designed to yield a vertical cross section of patches of discolored water injected by tidal flow through Deception Pass. Vertical color-infrared photographs of the sea surface were obtained as the patches were advected past the fixed sampling point. These observations are in general agreement with the initial results of a diagnostic numerical model (3-space and time) presently under development. (Smyth [Galt, Kelley])

## VII. Sediment Transport

The purpose of this element is to elucidate the phenomena of sediment movement in the marine environment. Investigations include theoretical studies of the dynamics of boundary-layer flows and associated grain movement; field experiments of natural flow conditions relating to sediment motion; and descriptive studies of the sedimentary processes in various marine environments (see also V).

### A. *An Integrating Nephelometer for Measuring Particle Mass Concentrations in the Deep Sea*

A self-contained, portable, and relatively inexpensive integrating nephelometer has been designed for use in the deep sea. It continuously measures the light scattered from suspended particles and with a suitable pressure housing can be lowered to any depth. The scattering profile is recorded internally. The nephelometer has been used for two years at 82 stations in depths from 200 to 2400 m. There are significant correlations between light scattering and concentrations of suspended inorganic particles collected by *in-situ* filtration. The instrument provides a rapid and reliable estimate of mass concentrations of particles in natural marine waters. (Sternberg, Baker, McManus, Smith, Morrison)

### B. *Continuous-Light Scattering Profiles and Suspended Matter Over Nitinat Deep Sea Fan*

During September 1971 and June 1972, a total of 65 light-scattering profiles were recorded in the waters over the Nitinat Fan by means of a self-contained, continuously recording nephelometer. All profiles extend from the sea surface to a point 20 m above the sea floor (maximum depth 2400 m). As many as 5 prominent scattering layers are observed within the water column at a given station. Some scattering layers can be traced over wide areas of the fan and appear on records from both cruises. The most persistent feature of the profiles, and the only one found on every record, is a bottom nepheloid layer (BNL), of steadily increasing light scattering, immediately below a layer of relatively clear water and immediately above the sea floor. The vertical extent and scattering intensity of the BNL (normalized to the scattering levels of the overlying clearer waters) change markedly over short lateral distances in a manner apparently related to fan topography. In general, the BNL thickens (>300 m) and intensifies (>2.5 x normal) over the topographic lows; it is most prominent above Cascadia Valley, the major valley crossing the fan, as well as above the nonchannelized, steep northern flank of the fan. Over the levees separating the smooth northern flank from Cascadia Valley to the south and over the foot of the continental slope which forms the eastern border of the fan, the BNL thins to <50 m, and the scattering intensity is <1.5x normal. (Baker, Sternberg, McManus)

### C. *Theoretical Studies*

In conjunction with turbulent boundary layer and coastal circulation experiments, we are examining the very foundations of sediment transport theory. Research on critical unsolved problems of multiphase flow is being

carried out. Past emphasis has been on erosion and deposition and the interactions with bedload transport; however, work on suspended sediment transport by unsteady and nonuniform flow studies are now being stressed. (Smith)

*D. Relation Between Wave Conditions and Sediment Resuspension*

At the same time as the observations of wave conditions on Cobb Seamount (see I B), Dr. Sternberg was conducting an experiment on bottom clarity on the Washington shelf. Therefore, we have been able to quantify the relation between the wave conditions at Cobb Seamount and sediment resuspension on the Washington shelf. This has led to a criterion for predicting sediment resuspension given the swell conditions.

The pressure gauge is currently in place at the Columbia River bar in an effort to study the wave conditions responsible for movement of the dredge spoils (see XXVI P). Recovery of the instrument is planned for late spring 1975. (Larsen)

### VIII. Marine Stratigraphy

Marine stratigraphy involves description, correlation, and interpretation of sediments and sedimentary rocks of the deep sea and continental margins. Information gleaned from this field is applied to the study of global tectonics, geological and climatic history, the evolution of planktonic life forms, and the economic potential of shelf and deep-sea areas, among other subjects.

#### A. *Postglacial History of Saanich Inlet*

A series of deep cores that sampled most of the section of postglacial sediment in Saanich Inlet, British Columbia has been examined. Previously a detailed radiocarbon examination was carried out by Yang and Fairhall, Department of Chemistry, and therefore the chronology of the cores is well known. The upper 20 m of varved sediment with a high diatom content has accumulated over the last 6,000 years indicating that the present hydrography that dictates intermittent anoxic conditions has been continuous for that period of time. Below 20 m, the sediment deposited before 6000 yrs B.P. and after about 10,500 yrs B.P. is either indistinctly varved or homogenous and contains relatively few diatoms. The occurrence of a fossil benthic fauna, which includes foraminifera, sponges, and echinoids, in the latter sediments suggests that the oxygen content in the bottom water was very low, but perhaps a little higher than that of the present Santa Barbara Basin, California. This stratigraphic record is being examined in the light of the known climatic and geologic history of the area with the aim of interpreting past hydrographic conditions in Saanich Inlet. (Echols and co-workers)

#### B. *Biostratigraphic Studies*

A rather complete series of Lower Miocene through Upper Eocene radiolaria in the Philippine Sea, and Pleistocene to Uppermost Miocene silicoflagellate and ebridian assemblages from the Sea of Japan were obtained through participation on Leg 31 of the R/V *Glomar Challenger* during June to August 1973 (Deep-Sea Drilling Project). The details of the microscopic examination of the microfossils are being incorporated as separate chapters in the Initial Reports.

A biostratigraphic value of the silicoflagellate datum indicating approximately 0.7 m.y. has been confirmed by its wide occurrence in the central and western subarctic Pacific, Bering Sea, and the Sea of Japan. Study of the stratigraphic distribution of planktonic microfossils (diatoms, silicoflagellates, and radiolarians) and paleomagnetic measurements for the core sediments are near completion. (Ling)

Siliceous microfossils from core sediments of Ross Island (Hole 3) and New Harbor (Holes 8 and 9), Antarctica obtained through participation in an international program, Dry Valley Drilling Project (DVDP), are also being investigated. (Ling)

#### C. *Paleontologic Synthesis of Cenozoic Deep-Sea Data*

The cores recovered by the Deep Sea Drilling Project are the major source of information on the geologic history of the oceans. Data from these cores have been published in the Initial Reports of the Deep Sea Drilling Project

and in numerous scientific journals. In addition, pertinent data are available in the files of the Deep Sea Drilling Project and of the laboratories which have studied samples from the cores.

By far the largest body of data is that published in the Initial Reports. Each volume in this series contains chapters on the physical properties, lithology, and paleontology of the fossil plankton of the cores, which have been prepared by a large number of scientists of widely varying interests. Subsequent studies of samples from the cores also have been highly varied both in goal and scope. In both the Initial Reports and the subsequent papers, standard classifications or terminology has not been used by either the lithologists or the paleontologists.

The first step in the synthesis, therefore, is to homogenize the data so that the results of each suite of investigators are directly comparable. The methods used to render the paleontologic and lithologic information into common form differ according to the nature of the available information. The goal of our analysis of the paleontologic data is a series of interrelated optimal biostratigraphic schemes for all or any part of the World Ocean. In producing a synthesis of the paleontologic information, two kinds of problems must be solved:

- 1) The specialists may have used different names for the same taxon and their ideas concerning the variability permitted within a taxon may have differed. To recover as much information as possible from the available data, specialists are critically examining the published data and synonymizing it into a nomenclaturally homogeneous body. Subsequent reexamination of material has been required in some instances.

- 2) The occurrence of plankton fossils in deep-sea sediments are a function not only of geologic time, but also of biogeography, environment of life, dissolution in the deep ocean, and changes which may have occurred within the sediment. To achieve the best biostratigraphic conclusions it is necessary to uncouple each of these factors, insofar as possible. This can be achieved by matrix analysis. The matrix analysis consists of a comparison of each biostratigraphic event (highest or lowest occurrence of a taxon) with other biostratigraphic events. Knowing the number of sections in which each pair of events occurs in superposition and the number of sections in which they occur in a given order, the maximum likelihood estimator and confidence interval for the probability that they will occur in the given order can be determined. Then, considering all possible chains of events for the interval being examined, the sum of the values of each of the maximum likelihood estimators divided by their confidence intervals is determined. The optimal chain is that with the highest sum and is *ipso facto* the longest, most reliable, and most widely distributed suite of events to be found in the section considered.

The initial phase of research (December 1972 - September 1973) was directed toward compiling a detailed computer-based library of published information about Oligocene calcareous nannofossil taxa; the main use is to summarize the "state of the art" and to infer where the collection of primary data would be most beneficial. This phase of research has been completed; however, the library will be updated continuously as new information is published.

Subsequently the research effort shifted to the primary collection of the additional data shown to be needed during the first phase. This was done mainly by optical microscope examination, supplemented by the scanning electron microscope, of calcareous nannofossils. Core samples were provided by the National Science Foundation through the Deep Sea Drilling Project. Analysis of these samples is now complete.

Table I shows the total number and geographic distribution of samples which have been analyzed. Figures 3 and 4 summarize some of our results and demonstrate the gain in resolution when internally consistent data is used for biostratigraphic subdivision.

Our initial conclusions are: 1) at any level of probability the biostratigraphic resolution in any given area (local or global) can be doubled using an internally consistent body of data when processed within a probabilistic framework; 2) sequences change appreciably among differing oceanic, climatic, and water depth regimes; 3) higher biostratigraphic resolution is obtainable at lower latitudes than at higher latitudes.

The overwhelming benefit of computer processed paleontologic data is that for the first time the minimal acceptable results may be specified before starting a project in order to estimate the amount of work necessary to accomplish the project. Conversely, one can also estimate the type of results a given amount of investigation can be expected to produce. (Worsley and students)

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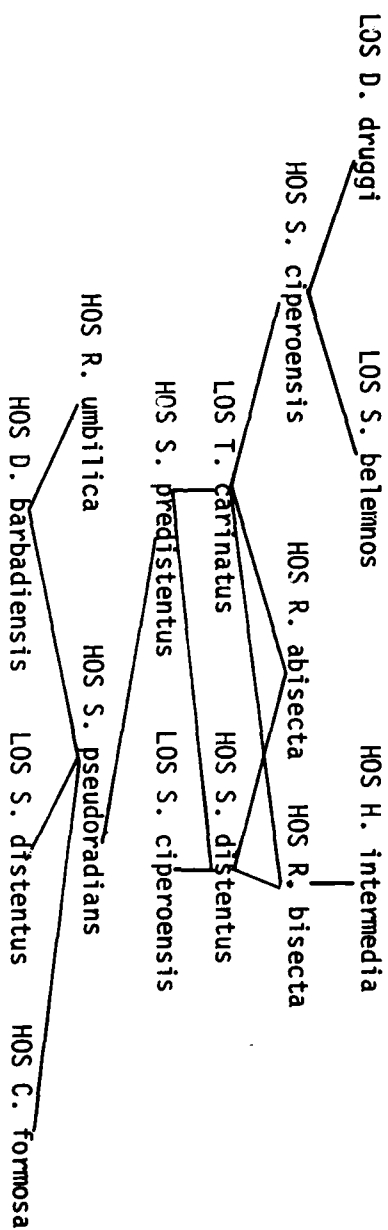


Figure 3. Probable stratigraphic sequences for global Oligocene nanofossils (published data) @ 0.95

This dendrogram represents the most probable stratigraphic sequences for global oceanic Oligocene calcareous nanofossils as determined from the data published in the Initial Reports of the Deep Sea Drilling Project. A link between two stratigraphic events (the lowest occurrence surface [LOS] or highest occurrence surface [HOS] of species) is depicted by a solid line and indicates that the two events occur in order with a minimum probability of 0.95 (0.00 = randomness and 1.00 = nonrandomness). Each link is analogous to a zone in the traditional sense; however, several pathways or alternate zonal schemes are apparent. The zonal scheme best suited for a particular region can be determined by the taxa present in the sediment, and also provides information on paleobiogeography, paleochemistry, paleoclimatology, dissolution, diagenesis, and other parameters which determine a species occurrence in a stratigraphic section.

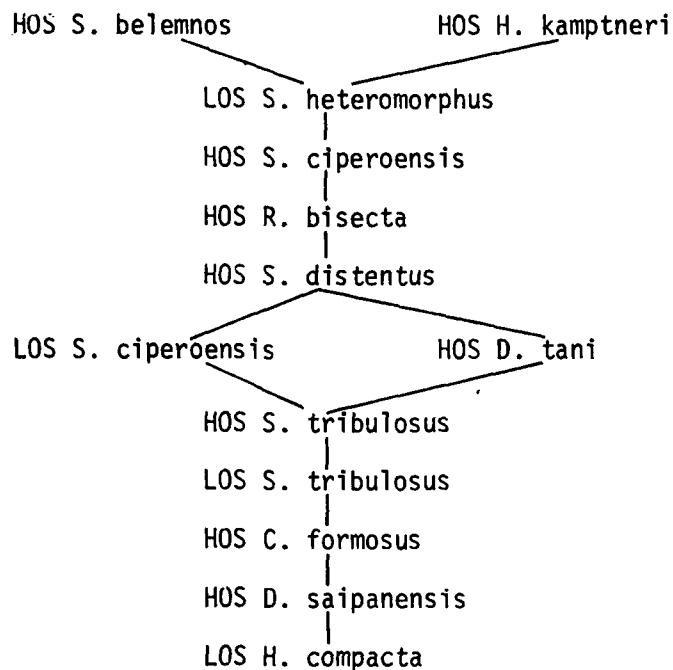


Figure 4. Probable stratigraphic sequences for global Oligocene nannofossils  
(original data) @ 0.95

This dendrogram represents the most probable stratigraphic sequences for oceanic Oligocene calcareous nannofossils. The dendrogram was determined from data collected by optical light microscopy on global Oligocene samples. The minimum link between events is 0.95 and the resulting dendrogram shows a significant increase in resolution for internally consistent data in comparison to the dendrogram based on data published by the Initial Reports (Figure 4). Artificial truncation of the data at the top and bottom of the sequence may result in inaccuracies in species ranges.

## IX. Coastal and Shelf Sedimentology

The purpose of this element is to investigate the sedimentological nature of estuarine and continental shelf environments. Studies include the origin and classification of sediments, distribution of sediment types, rates of deposition, and interpretations of the geological history of shallow marine environments.

### *A. Heavy Minerals of the East-Central Bering Sea Continental Shelf*

A factor analysis of 51 grab samples from the east-central Bering Sea continental shelf identified three factors that account for 88 percent of the variation in the relative amounts of the nine major heavy mineral groups that were used as variables. The most important components for definition of the sources and processes which have determined the properties of the surface sediments in this area are epidote, garnet, and opaque minerals, and clino-pyroxene and weathered grains for Factors I-III, respectively. The occurrences and textural associations of Factors I-III sediments indicate that the relative fractions of the characteristic minerals have been largely determined by sorting; proximity of source is more important along the Alaskan mainland. Throughout the area, the heavy mineral contents of samples differ from those of modern Yukon River sediments. This study demonstrates the utility of factor analysis in the interpretation of relatively uniform heavy mineral data. (Knebel [Creager])

### *B. Holocene History of the Laptev Sea Continental Shelf*

The 400-km wide, low gradient Laptev Sea continental shelf consists of flat terrace-like features at regular depth intervals from 10 to 40 m below present sea level. The five large submarine valleys traversing the shelf do not grade continuously seaward, but contain elongate, closed basins. These terraces and closed basins plus deltaic sediments associated with the submarine valleys quite possibly mark sea level still stands and enable reconstruction of the paleogeography of the Laptev Sea shoreline at five periods during post-Wisconsin (Holocene) time.

Radiocarbon dates on the silty clay to clayey silt sediments from cores of the northeastern Laptev Sea indicate average sedimentation intensity of 2 to 15 mg/cm<sup>2</sup>/yr. The presence of manganese nodules and crusts in samples from depths less than 55 m and a general decrease in total foraminiferal abundances with depth suggest that the present deposition rate is less than when the sea level was lower. The main components of the shelf deposits are nearshore sediments which were spread over the shelf as Holocene sea level fluctuated and marine currents distributed modern fine sediment. Rare silty sand layers and the coarser nuclei of the manganese crusts and nodules indicate ice rafting. However, this mechanism is probably only locally important as a significant transporting agent. (Holmes, Creager)

### *C. Recent Sediments of Puget Sound and the Outer Continental Shelf*

The character and distribution of suspended particulate matter and of specific components of surface bottom sediments will be examined in the central basin of Puget Sound and on the outer continental shelf. An initial experiment will attempt to determine an "optical signature" for suspended particulates associated with outfall wastes and to distinguish these from naturally occurring river input and marine detritus. Subsequent studies will attempt to establish links between the mineralogy and chemistry of the surficial bottom sediments and the distribution of these parameters in the suspended particulate matter. (Burns, Baker)

#### *D. Recent Sediments of the East Siberian Sea*

The East Siberian Sea, one of the large epicontinental arctic seas off northeastern Siberia, is shallow and covered with ice for most of the year. The sea bottom is monotonously flat except where intersected by two drowned river valleys. The surficial sediments are fine grained, often containing over 19% colloidal (finer than  $11\phi$ ) material. This is attributed to the mechanical weathering in the arctic permafrost region, the low gradients of incoming rivers, and the low energy conditions in the East Siberian Sea. The primary sources of sediment are the Indigirka and Kolyma rivers and the New Siberian Island region. Sediment transport is generally easterly to northeasterly. On the basis of factor analysis of grain size data and heavy mineral analysis of the  $4\phi$  sand fraction, three distinctive sediment groups have been defined within regions corresponding roughly to the western, central, and eastern portions of the East Siberian Sea. Sediments derived from the New Siberian Islands dominate the shallow (10 to 15 m) western region; currents are higher than average and silt is the dominant sediment type. The central plateau is dominated by material introduced by the Indigirka River, characterized by low concentrations of heavy minerals. Currents are generally weaker than in the New Siberian Shoal region and sediments are typically clayey silts. Zones of cleaner silts indicate locally more intense currents. The eastern region is characterized by relatively deep (30 to 50 m), irregular topography and variable sediment texture and mineralogy. Winnowed sandy sediments and gravelly sandy muds, possibly associated with ice rafting, break the pattern of silty clays and clayey silts. The Kolyma River has introduced most of the sediment in this region although local shoreline sources are indicated clearly by the mineralogy. Ice rafting generally appears to be insignificant in the East Siberian Sea sediments. (Naugler, Siberverg [Creager])

#### *E. Modern Sediment and Benthic Foraminifera of the Southeastern Bering Sea Continental Shelf*

Extensive acoustic-profiling records have enabled us to revise the bathymetric chart of the southeastern Bering Sea continental shelf. Factor analysis of sediment texture has identified five factors with distributions and associated sediment characteristics in accord with available physical oceanographic data and published sediment transport models. Sediment characteristics in water shallower than 50 to 60 m suggest the influence of active resuspension, whereas deeper sediments appear to be controlled by settling velocity and distance of transport. Mean sediment transport is strongly downslope in Bristol Bay and northward and contour-conforming elsewhere. Distributions of five biotopes, defined from foraminifera faunas, reflect both hydrologic conditions and the nature of the substrate. (Askren [Creager, Echols])

## X. Micropaleontology of Sediments

The program is directed toward a better understanding of the major siliceous and calcareous components of marine sediments. The taxonomy, evolution, ecology, and distribution of each major group of organisms, in space and time, are being investigated.

### A. *Silicoflagellate and Radiolarian Studies*

Since the documentation of silicoflagellates and ebridians from the Late Cretaceous and Cenozoic, in 1972, which enhances the stratigraphic potentiality of these groups in deep-sea sediments, research in this field has been intensified to refine the zonation and to add documentation as new information is now available.

Samples collected by the Deep Sea Drilling Project in the eastern North Pacific during Legs 5, 16, 17, 18, and 19 are being analyzed for the comparative study of the high and low latitude assemblages and for correlation with several Californian Tertiary land sections.

The first recovery of Cretaceous sediments from the Arctic Basin was reported during 1973 based on the contained silicoflagellate assemblage. Analyses of samples from Denmark, California, New Zealand, and deep-sea sediments from the North Atlantic Ocean, which encompass the majority of the Eocene interval, suggest more confidently a Paleocene age for another core from the Arctic Basin. Discussions with Russian scientists during the III Planktonic Conference at Kiel, West Germany in September 1974 further corroborated the above age determination.

Late Mesozoic radiolarian assemblages have been recovered from cherts of Vancouver Island, Canada; Whidbey Island, Washington (with graduate students of the Department of Geological Sciences); and from several localities of south-east Asia (with Dr. Neville S. Haile, University of Malaya). Detailed examination of the radiolaria, including observations with the scanning electron microscope, should be a help in defining the age more closely. Precise dating will be of great significance to the geohistory of the respective areas. (Ling)

### B. *Arctic Sublittoral Foraminifera Studies*

Distribution patterns of benthic foraminifera on the Alaskan shelf and slope of the Beaufort Sea have been found to be zoned with respect to water depth and distance from shore. A central shelf zone from about 15-20 m to 35-40 m may be associated with the region of the shelf below the fast ice-pack ice shear zone where ice gouging of bottom sediments is maximum. Diversity did not vary with depth from the inner shelf across the upper slope to about 1500 m. Diversity on the shelf was higher than for temperate latitudes but lower than for tropical latitudes. These findings support latitudinal trends in species diversity reported by Buzas and Gibson on the basis of limited arctic data.

Time-series analyses of test size and abundance of *Elphidium clavatum* from lagoon stations show that this species reproduced continuously throughout the summer season. Populations were decimated in early winter after sea ice formed and became fully reestablished only after mid-July.

Paleontological studies of box cores, in cooperation with U. S. Geological Survey personnel, have shed light on the conditions resulting in the formation of ice-rafted gravel deposits on the outer shelf. Lutite sediment beneath the gravel deposit at 118 m water depth was deposited as sea level rose following the last glaciation; water depth was at least 40 m prior to deposition of the gravel. Exact circumstances leading to initiation of gravel deposition is still poorly understood. (Echols, Kachel)

## XI. Global Tectonics

This program involves the use of marine geophysical techniques in the study of the large-scale tectonic processes. Historically, the method is not very old (post World War II), but it has already resulted in a great unifying theory for geophysics and geology: the plate tectonics explanation of continental drift. The new concepts have already revolutionized research on earthquake prediction, and regional prospecting for minerals and oil.

### *A. Tectonic Movements near Plate Boundaries*

An excellent library of acoustic reflection profiles of several sections of the Pacific Ocean margin will be used to investigate the mechanism by which plate is "subducted" or removed from the earth's surface. Comparison can be made to similar profiles across a sedimented spreading center where the oceanic lithospheric plate is being created at several cm/yr. Additionally, heat-flow measurements in and near trenches will be examined for information about the age of the flat-lying sediment fill found in some trenches, and the manner in which surficial material may be incorporated into island-arc ridges or continental margins. (Lister)

### *B. Geophysical Studies of the East Pacific Rise*

The third (and probably final) cruise to the East Pacific Rise off Acapulco (see Figure 5) to investigate the crustal and upper mantle structure of a ridge and how these structures change with distance, and hence age, from the ridge axis was in March and April 1974 (TT 088). It was particularly productive of data and benefited from the cooperation with several other investigators and institutions. Dr. LeRoy Dorman, Scripps Institution of Oceanography, collected data on the ship with his Askaniian gravity meter while on land Dr. Charles Helsley, University of Texas, Dr. Bob Meyer, University of Wisconsin, and a group from the University of Mexico set up arrays of seismometers to detect the sound waves generated by the explosions at sea. By combining our seismic data, as recorded on ocean bottom seismometers and telemetering buoys, with the land seismic data, we are hopeful that more information on the structure of the Middle America Trench will be forthcoming.

The ages of the rocks and the spreading patterns from the East Pacific Rise to the Trench will be determined from the magnetic data while the data from the 40 seismic refraction lines that were shot will be used to study in detail the crustal structure and the upper mantle velocity and anisotropy and their age dependences. By combining the seismic results with Dorman's gravity data, we hope to further investigate the mechanism of sea floor spreading. (Lewis)

### *C. Tectonics of Island Arc Regions*

Recently, paleomagnetic studies have been completed in the Marianas District, Micronesia. These studies in conjunction with those of other island arc regions suggest that substantial bending of segments of island arcs sometimes occurs after the arcs have formed. The emphasis of the continued study is an attempt to find out how such deformations occur. (Merrill, Lister, Lewis)

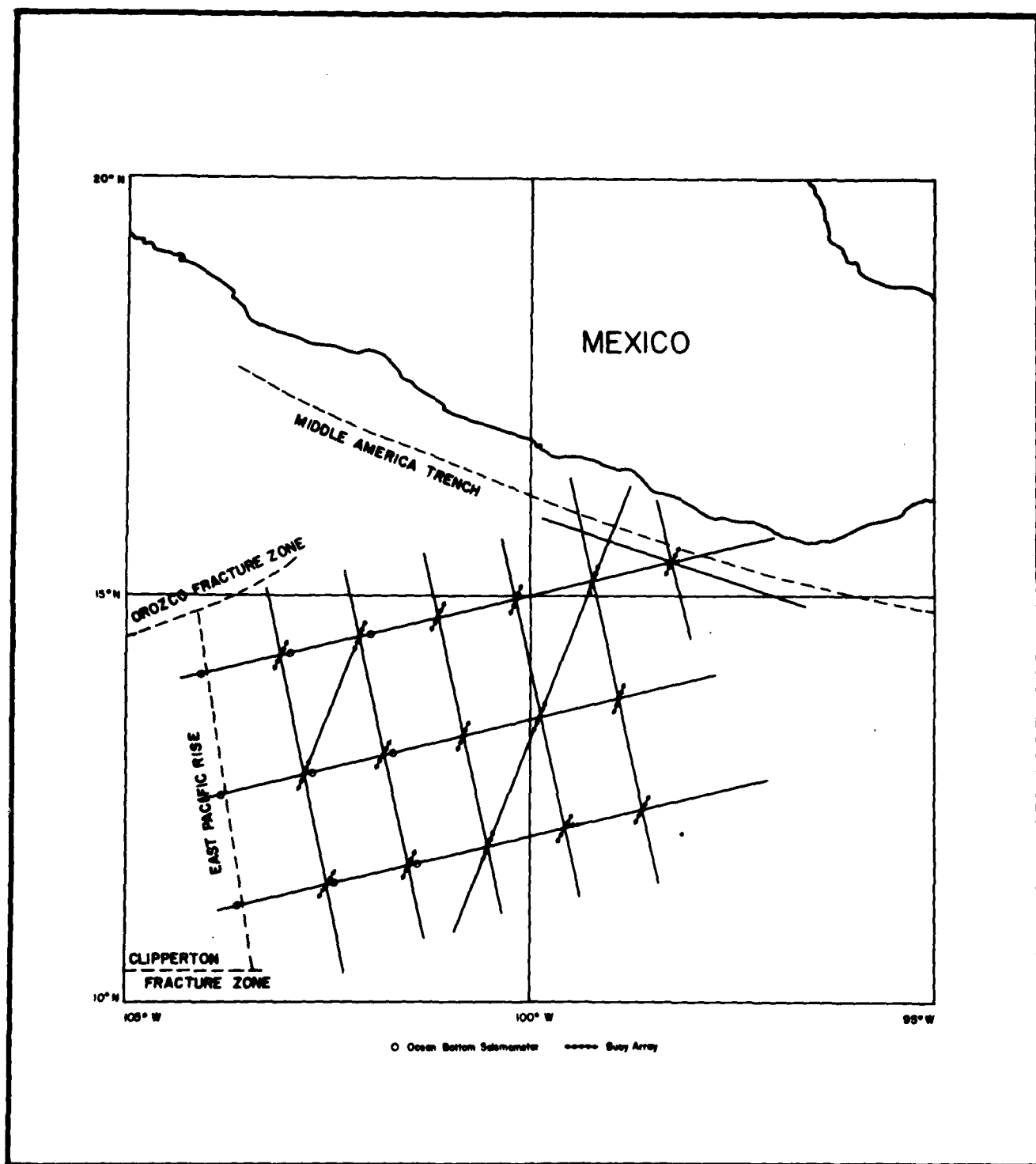


Figure 5. Location of seismic refraction lines shot between the East Pacific Rise and Middle America Trench

## XII. Genesis of the Oceanic Crust

This element, another aspect of marine geophysical investigation, seeks to determine the structure of the oceanic crust itself and how this varies with time after its creation. Besides the inherent scientific interest of this as yet unsolved problem, there are potentially important deductions to be made about ridge crest thermal and mineralization processes. Magnetic and seismic studies under way will help determine the structure and geological history of the oceanic crust.

### *A. Geothermal Phenomena near Mid-Ocean Ridge Crests*

Efforts to interpret an exceptionally detailed geophysical survey of the north end of the Juan de Fuca Ridge are continuing. Knowledge of the heat-flow and of the sediment structure over 10,000 km<sup>2</sup> of the ocean floor is being combined to estimate rock basement temperatures associated with different zones of a sea-floor spreading center. This entails the derivation of some new theoretical heat-flow solutions as well as an intimate familiarity with the data. Meanwhile, an independent theoretical investigation has suggested that seawater can penetrate into hot rock at the surprisingly rapid rate of 30 m/yr or more, many times the sea-floor spreading rates of a few cm/yr (Figure 6). Thus enormous, if highly localized, geothermal powers may be generated near a ridge crest, and it is hoped that the interpretation of the survey will lead to an estimate of where to search for such phenomena. (Lister)

### *B. Ocean Bottom Seismometry*

We have recently developed some cheap ocean floor seismometers that are dropped from the ship and collected after a preset interval. They have been used as receivers for both surface and bottom explosive shots to determine the structure near the crest of the Juan de Fuca Ridge in greater detail than possible by means of surface sonobuoys. They also recorded natural earthquakes in the area of emplacement. The instruments have been used also to supplement sonobuoy data in an extensive survey of crustal structure near the East Pacific Rise off Mexico, in some cases providing reversal for long refraction lines. A small array received a two-dimensional pattern of 250 shots over a carefully selected smooth piece of moderately young (8 M yr) ocean floor, and we hope to determine the detailed velocity structure of the oceanic crust, both to compressional and to shear waves. Comparison of these data with measurements of rock samples by Dr. Christensen, Department of Geological Sciences, will perhaps result in an identification of the rock types present in the oceanic crust. (Lewis, Lister)

### *C. Paleomagnetism and Rock Magnetism of Deep-Sea Sediments*

Paleomagnetic studies and rock magnetic studies of Pacific Ocean sediments are being undertaken to determine the origins of remanence in deep-sea cores and to use the remanence to gain insight into the history and tectonics of the oceanic crust. (Merrill)

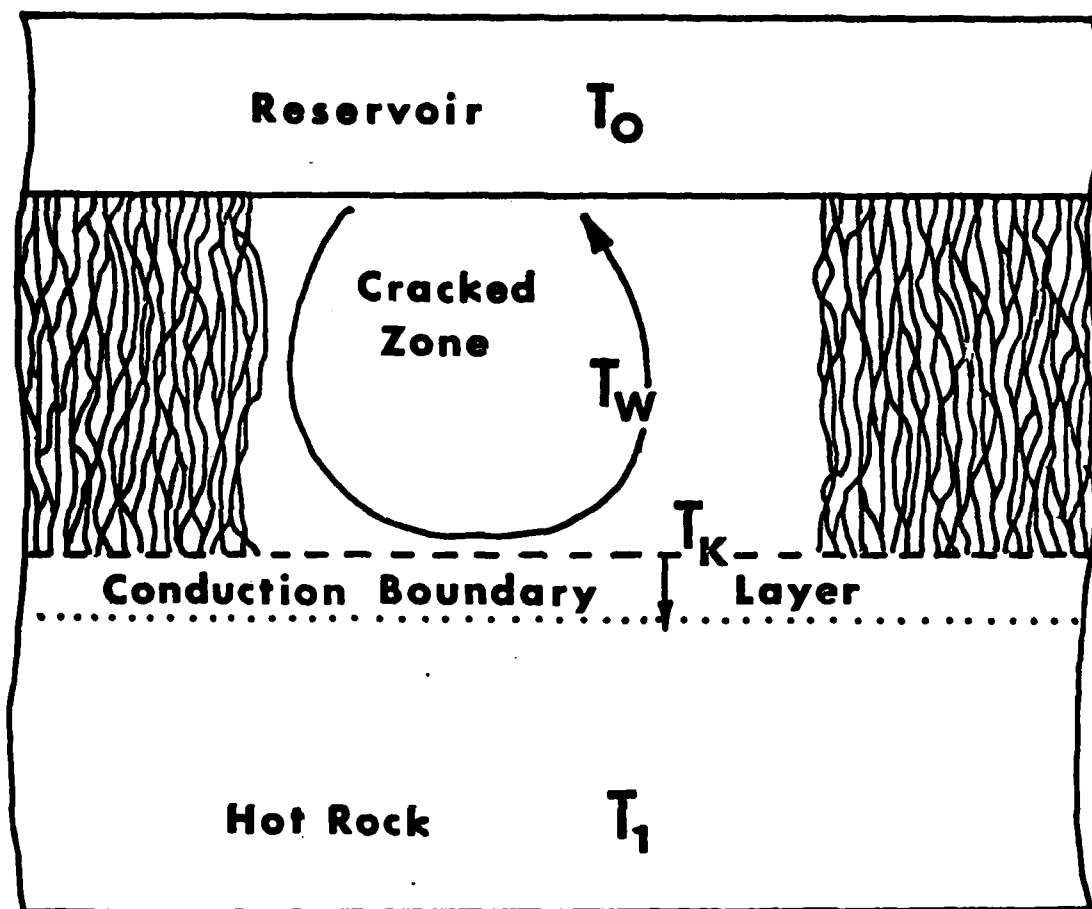


Figure 6. A one-dimensional model of the penetration of water into hot rock

It is characterized by a cracking front (temperature  $T_k$ ) where rock becomes brittle enough to crack in tension as it cools. The critical parameter defining the system is the velocity of propagation of the front.

#### *D. Geomagnetic Secular Variation Studies*

Paleomagnetic field studies on oceanic island basalts and theoretical studies involving the origin and history of the earth's magnetic field are under way. The objectives are to add to the knowledge of the earth's dipole and nondipole magnetic fields and to clarify some of the assumptions on which paleomagnetism is based. (Merrill)

#### *E. Origin of Remanent Magnetization in Igneous Rocks*

Experimental and theoretical studies on the origins and properties of magnetization in minerals and rocks are continuing. The range of the studies is wide as indicated by a few examples: the use of an oxygen plasma to study magnetic changes in magnetic minerals on oxidation; detailed magnetic and chemical analyses of various igneous rocks to identify the mineral compositions responsible for various magnetic properties; theoretical studies of the factors controlling magnetic stability. (Merrill)

### XIII. Analytical Chemistry of Seawater

All the research aspects of chemical oceanography require an accurate description of the chemical field--a problem in analysis. Analytical methods adequate to the task are required and often must be developed and adopted specifically to marine problems or developed *de novo*.

#### A. Excess Nitrogen Estimates via $N_2$ -Ar Ratios

Methods have been developed for extraction of gas from water samples and the determination of the  $N_2$ -Ar ratio by mass spectrometry. Samples from five stations in anoxic basins were used for gas analyses. The excess nitrogen values compare well with a model of the nitrogen available for denitrification. Additional information on the methane concentration in the basins has been obtained by measuring the  $CH_4$ -Ar ratio. (Pough)

#### B. Methodology of Enzyme Assays and Laboratory Studies

##### 1. Solubilized zooplankton assay

The original electron transport system (ETS) assay has been modified by the addition of Triton X-100 to the reaction mixture. This eliminates organic extractions necessary in the original method and increases the sensitivity by a factor of 5. This solubilized assay has made possible the study of pressure effects on ETS activity in zooplankton. (Owens [King, Packard])

##### 2. Solubilized bacteria assay

A similarly modified assay is being developed for the study of marine bacteria. Preliminary results indicate increased sensitivity and adaptability to the study of pressure effects on bacterial ETS activity. (King, Packard)

##### 3. Sediment assay

A method for releasing enzymes from viable material in nonreducing sediments utilizing sonification techniques has been developed. The method gives comparable activity to that of conventional grinding methods but is more versatile and is not affected by the amount of sediment in the sample. (Christensen, Packard)

##### 4. Biomass estimation

We are increasingly aware of the need for a rapid and sensitive biomass index. Thus, we are investigating the feasibility of adapting the fluorescamine assay for amino acids for oceanographic field use. Although some difficulties remain, the preliminary experiments are promising. Chemostat cultures of *Skeletonema costatum* have been tested, yielding results comparable with the Lowry method. The precision of the methods is about the same, but the fluorescamine assay is an order of magnitude more sensitive and requires about 100 times less sample. Protein concentrations as low as 0.2  $\mu\text{g/l}$  (about 100 cells/l) can be detected with a sample volume of 300 ml. (Dortch [Ahmed, Packard])

## 5. Automated enzyme analysis

We have designed, constructed, and tested in the field (JOINT-I, CUEA) a semi-automated analysis for ETS. (Abrahamson [Packard])

## 6. Electron transport system calibration

Zooplankton: Respiration and the activity of the respiratory electron transport system were measured in 15 species and several mixed populations of marine zooplankton. The correlation between the two parameters was high and sufficient to predict respiration to within  $\pm 36\%$ . It is partially species dependent but independent of size and temperature. (King, Packard)

Bacteria: The relationship between oxygen consumption, ETS, and ATP in cultures of three species of marine bacteria is being investigated. R/ETS and ETS/ATP ratios increase during the transition from the log phase of growth to the senescent phase. They level off at  $0.476 \pm 0.023$  and  $0.21 \pm 0.012 \mu\text{l O}_2\text{hr}^{-1}\text{ng ATP}^{-1}$ , respectively. We reason that these factors are applicable to deep-sea bacteria. (Owens [Christensen, Packard])

Phytoplankton: The measurement of a respiratory control index is useful in determining the energy balance in respiration. The index is the ratio of the rate of respiration *in vivo* to the calculated maximum rate of oxygen consumption *in vitro* as measured by the enzymatic ETS rates. In calculating *in situ* oxygen consumption in a water parcel, the ratio R/ETS must be fairly constant. Our results indicate that the ratio is constant in nine species of phytoplankton. Occasionally, lower R/ETS ratios have been obtained but in each case the culture was unhealthy. (Ahmed, Kenner, Packard)

Relationship between ETS activity and denitrification: Using ETS activity data obtained on Cruises TT 066 and TT 076 and the relationship between ETS activity and the rate of denitrification determined in the laboratory, the rate of denitrification in the eastern tropical North Pacific has been estimated as  $2 \times 10^{13} \text{gN/yr}$ . This is in excellent agreement with the two previous measurements of 2 to  $3 \times 10^{13} \text{gN/yr}$  and  $1.6 \times 10^{13}$ . (Devol, Packard)

Comparison of ETS method with standard hydrographic techniques: Oxygen utilization in the entrapped deep waters of Dabob Bay, a fjord off Puget Sound, was measured by both standard hydrographic techniques and the ETS method during two months of nonflushing conditions. The rate of *in situ* oxygen utilization by the hydrographic technique was  $1.2 \mu\text{g-at O}_2\text{day}^{-1}/\text{l}$ , by the ETS method  $0.86 \mu\text{g-at O}_2\text{day}^{-1}/\text{l}$ . The relative contribution of the net plankton, ultra plankton, and benthos to this rate was 24%, 44%, and 32%, respectively. (Christensen, Packard)

## 7. Glutamate dehydrogenase studies

A modified fluorometric assay that is sensitive enough to detect the low levels of glutamate dehydrogenase (GDH) activity encountered in both field and laboratory studies has been developed. The GDH assay has been standardized and its kinetics characterized with regard to the substrate, temperature, and biomass parameters. Detailed kinetic experiments have been carried out in three diatom species, one belonging to the Chlorophyceae, and two to the Chrysophyceae. During the course of this study an NADH-dependent isozyme of

GDH was discovered. The relationship of this enzyme to the biosynthetic NADPH-dependent GDH activity is currently under investigation. (Ahmed, Packard)

#### 8. Amylase studies

An assay for amylase activity has been adapted to measure zooplankton grazing. This assay will be used in the grazing assessment program in the Peruvian upwelling expedition (JOINT-II, CUEA) in 1976. (Griffiths [Packard])

#### 9. Temperature studies

The effect of temperature on the respiratory electron transport system in plankton was studied in populations collected between 10° and 45°N in the eastern Pacific Ocean. The results yielded Arrhenius activation energies of  $15.8 \pm 2.8$  kcal mole<sup>-1</sup> for microplankton, 16 kcal mole<sup>-1</sup> for epipelagic zooplankton, and 13.2 kcal mole<sup>-1</sup> for bathypelagic zooplankton. The differences between these values were not statistically significant. The respiratory electron transport activity and the Arrhenius activation energy in the microplankton from the euphotic zone ranged from 0.12 to 0.65  $\mu$ l O<sub>2</sub> l<sup>-1</sup>hr<sup>-1</sup> and from 11.7 to 21.9 kcal mole<sup>-1</sup>, respectively. Neither parameter varied systematically with temperature. (Devol, King, Packard)

#### C. *Protein Determination*

A fluorometric assay for protein and amino acids that is three orders of magnitude more sensitive than existing methods has been developed. The protein assay was used successfully on the JOINT-I expedition to the northwest African coast. (Dortch [Packard])

#### D. *Nutrient Uptake Determination*

A <sup>15</sup>N tracer technique is being used to determine nutrient uptake by marine phytoplankton. The <sup>15</sup>N technique is followed by mass spectrometry. This method is useful on board ship as well as in the laboratory. (Pavlou)

#### E. *Towed Underway Pumping System*

Another of the projects under way in the studies on nutrient and phytoplankton fields is the development of a towed underway pumping system (TUPS) to provide information on the vertical distribution of nutrients and phytoplankton as well as *in situ* temperature and salinity measurements with the ship underway at typical mapping speed (8-10 knots). (Whitledge, Kelley)

#### XIV. Chemical Indicators of Oceanographic Processes

A function of chemical oceanography is the use of chemical variables to elucidate oceanographic processes. Such studies as the characterization and tracing of water masses and the reconstruction of biological events by following spatial and temporal changes in biologically mediated chemical variables are examples of this kind of research.

##### *A. Water Mass Characterization and Tracing in the Eastern Equatorial Pacific*

An isentropic water mass analysis using inorganic chemical variables has been completed for a set of observations obtained during the late fall of 1971 between the Galapagos Islands and the coast of Ecuador. Three water masses, one from north of the equator, one from south of the equator, and Cromwell Current water, were identified in the area. The Cromwell Current split into two major branches at the Galapagos Islands. Part of the flow passed the northern side of the islands and extended to the coast as a wide tongue that decreased in thickness by a factor of 5. The second branch extended south of the islands to the southern border of the cruise track at 3°S. A scale analysis indicated horizontal mixing was the dominant process controlling the distributions of chemical properties in the depth zone of the Cromwell Current. (J. Anderson, Richards)

##### *B. Structure and Circulation of the Costa Rica Dome*

A similar analysis is being made on data collected during the winter of 1973 in the vicinity of the Costa Rica Dome at 9°N and 89°W. In this study two water types, one associated with the North Equatorial Counter Current and the other with water of the oxygen minimum zone, have been identified. In the area of the dome these water masses reside as a number of large isolated particles in juxtaposition to each other. Characteristic horizontal and vertical scales are on the order of  $10^4$  and  $10^2$  meters, respectively.

Other studies of the structure and circulation of the Costa Rica Dome and rates of oxygen consumption in the region of the dome are based on the distribution of biochemical variables. These are discussed under "Enzyme Assay Estimates" in the following section. (J. Anderson, Richards)

## XV. Chemical Controls and Consequences of Biological-Biochemical Processes

The limitation imposed on photosynthetic productivity in the oceans by the availability of light and plant nutrients is an historical problem in oceanography. Newer developments are revealing a large variety of chemical controls on biological functions. These include the complex questions of the role that trace materials, such as metals and trace organic compounds, play in biostimulation or toxification of marine communities; and their effects on such basic processes as photosynthesis, ATP formation, electron transport system activity (ETS), and nitrate reduction and denitrification.

### A. Enzyme Assay Estimates

The vertical gradient ( $dR/dz$ ) of the oxygen consumption rate in the Costa Rica Dome, as estimated from electron transport system activity, at depths between 100 and 3000 m is better described by the equation

$R = R_0 e^{-\alpha \ln z}$  than by the equation  $R = R_0 e^{-\alpha z}$  suggested by Wyrski and Ben Yaakov. The horizontal gradients over the same depth range are variable and reach as high as  $0.55 \mu\text{l O}_2 \text{ yr}^{-1} \text{ l}^{-1} \text{ km}^{-1}$ . This value is nearly the same as  $dR/dz$  between 2000 and 3000 m ( $1 \mu\text{l O}_2 \text{ yr}^{-1} \text{ l}^{-1} \text{ km}^{-1}$ ). The direct measurement of these gradients tends to refute the argument that deep-sea metabolic activity is unvarying.

The vertical gradient in the ATP, the living fraction of the particulate organic carbon (POC) concentration, is described by the equation:

$\text{ATP}_z = \text{ATP}_0 e^{-\beta \ln z}$ , that is, the same form as the equation for oxygen consumption. Furthermore, the constants  $\alpha$  and  $\beta$  are similar in value ( $\alpha = 0.89$  and  $\beta = 0.81$ ), suggesting a close relationship between the two variables.

The elevated ETS activity observed in the oxygen-minimum zone reflects the enzymatic reorganization associated with the transition from oxygen utilization to denitrification. This conclusion is supported by the absence of an ATP maximum in the same water column and also by observations of elevated ETS activity in chemostats of denitrifying bacteria.

Below 200 m, concentration of POC remains constant. However, the absolute values are greater than normal oceanic values by a factor of 5 (40 g C/l as compared to 8 g C/l). This enhancement of POC under the Costa Rica Dome may be associated with the elevated productivity in the surface waters of the region. (Devol, Packard)

### B. Limiting Oxygen Tensions

A chemostat has been designed with dissolved oxygen as a controllable parameter, thus allowing the growth rate of bacteria to be limited by a carbon source while providing independent control of dissolved oxygen. Oxygen tension is monitored using autoclavable electrodes. This type of control permits the simulation of oxygen-deficient environments within which the growth rate of organisms is carbon limited, which may be the case in the region of the secondary nitrite maximum in oxygen-deficient environments.

Nitrate reducing and denitrifying bacteria have been isolated from several oxygen-deficient or anoxic marine environments. Chemostat studies are being carried out with these organisms to elucidate their physiological response to low oxygen concentrations by monitoring indices such as the level of respiratory enzyme activity, ETS, ATP, cell yield, and rates of oxygen and nitrate consumption. The resultant physiological data will allow us to interpret field data more intelligently and to model the processes responsible for the generation and maintenance of water masses with low concentrations of dissolved oxygen.

The kinetics of oxygen uptake have been determined for nine species of marine bacteria. In general, kinetic constants agree with those that have been determined for terrestrial and enteric bacteria. The kinetic constants indicate that bacteria from the eastern tropical North Pacific have a higher affinity for dissolved oxygen than those from the oxygen minimum zone of Saanich Inlet, British Columbia. Thus the oxygen concentration at which these organisms switch from oxygen to nitrate respiration is probably lower in the eastern tropical North Pacific than in Saanich Inlet. This observation is supported by observed distributions of secondary nitrite in the two areas.

Bacteria have been isolated from open ocean and nearshore oxygen-deficient or anoxic environments; the genera *Vibrio* and *Pseudomonas* have been identified. A *Vibrio* sp. from Saanich Inlet has been grown in both batch and chemostat cultures to relate *in vitro*, growth related, specific denitrification rates to denitrification rates observed by other investigators. Nitrate reduction beyond nitrite was inhibited by the presence of nitrate, as is often the case in confinement experiments of mixed populations.

Continuous culture of a pseudomonad, isolated from Lake Nitinat, British Columbia, has shown that for this organism:

- 1) Nitrate is preferred to ammonia when both are present in the medium.
- 2) Nitrite, at a low level, is found in the reaction vessel when the cells are reducing nitrate anabolically in the presence of high oxygen tensions.
- 3) The production of nitrite by oxygen-unadapted cells shows an initial increase at an oxygen concentration of approximately 16  $\mu\text{g-at/liter}$ ; maximal nitrite production occurs at approximately 6  $\mu\text{g-at/liter}$ .
- 4) The activity of the electron transport system on a cell-specific basis is approximately 2.5 times higher during dissimilatory nitrate reduction than during aerobic growth.
- 5) The cell yield (viable count) of carbon-limited growth during anaerobic growth is approximately 80% of aerobic growth.
- 6) The reduction of nitrate beyond nitrite occurs in the presence of nitrate but in the absence of oxygen.

Work is continuing with the objective of determining *in vitro* interactions of processes at low oxygen tensions which may help interpret field observations made in oxygen depleted and anoxic environments. (Martin, Ozretich [Richards])

#### C. Role of Trace Metals and Their Speciation in Photosynthesis and Respiration

Efforts have been made to develop the analytical methods, as well as conduct laboratory and field studies, necessary to understand the role of trace metals in photosynthesis and respiration. These studies involve

detailed examinations of trace metal speciation, particularly the capacity of seawater to chelate metal (copper) ions, and the characterization of the organic ligands.

Voltammetric studies at sea over a three-year period have resulted in correlations of metal chelation capacity with water type, productivity, enzyme activity, and other biological parameters. Studies on different water types, namely coastal and newly upwelled water off Oregon, the Columbia River plume, and Saanich Inlet, British Columbia, Los Angeles Bight, and Baja California water, have shown that biological productivity is not only responsible for the observed chelation of copper and lead but also may contribute particulate material that results in surface sorption of metals on colloids.

The studies include determining the temporal-spatial distribution of organic chelating species and characterizing them by molecular weight and functional group analyses. Samples from surface, deep, and interstitial waters of Narrows Inlet and from the entire water column of Saanich Inlet, both in British Columbia, are being so analyzed. Voltammetric titrations indicated significant organic chelation only in samples from the upper 10 meters of Saanich Inlet in June. Gel filtration separations of organic matter from pore waters, surface waters, and anoxic waters showed that the complexing capacity of pore waters decreased with depth in the anoxic sediments of Narrows Inlet. Copper and, to a lesser extent, lead were complexed with organic matter with molecular weights ranging from 500 - 10,000 in pore waters from the upper part of the sediment. However, the complexing capacity of the deeper pore water was low. The surface waters of Saanich Inlet contained excess nonlabile organic ligands of high molecular weight. The material was of lower molecular weight than that from the pore waters. Anoxic waters contained no significant chelating material.

Organic fractions with a measurable chelating capacity are being studied to determine the rates of metal uptake, as well as to further characterize the possible ligand species, using high-speed liquid chromatography. (Sugai [Healy])

#### *D. Effects of Copper on Biological Processes*

Measurable changes in the metabolism, respiration rate, and abundance of phytoplankton would be expected as a result of stress induced from a pulse-like addition of copper. We are endeavoring to observe the various responses to increasing amounts of introduced metal in both eutrophic and oligotrophic natural systems. The relationship between the responses and the speciation of the copper present is also being examined.

A preliminary study during TT 066-67 cruises showed an immediate and dramatic repression of photosynthetic carbon assimilation upon the introduction of parts per billion of copper. Generally this reaction was followed by an increase in respiration rate and ATP production, apparently as a protective response, either to counteract or to withstand the higher levels of copper. The natural populations studied could sustain these increased rates until the copper concentration reached the part per million level at which mortality occurred.

Laboratory semicontinuous batch cultures are being used to monitor the effect of copper on single species populations. The chemical speciation of the copper is being examined as is the response of the organisms in both eutrophic and oligotrophic water. (Lowman, Healy)

## XVI. Kinetics and Thermodynamics of Chemical, Biochemical, and Geochemical Processes

This section encompasses research on fundamental reactions in seawater, diffusive processes, and the chemical effects of specific conditions in the marine environment.

### A. Chemistry of Pore Waters of Sediments

Two mechanisms have been proposed most frequently to account for the higher enrichment of trace metals in deep-sea sediments than in those deposited near shore. The enrichment is the result of the transport of fine-grained detritus originating in rivers and streams to mid-ocean areas or by adsorption from seawater on iron and manganese oxides. It is difficult to evaluate these pathways because we know little about the trace metal contents of the suspended load of streams, their fate in estuaries, or the nature of their interactions with hydrous iron oxide. We are currently studying these two mechanisms.

A sampler that extracts water from the sediments *in situ* is being used, thereby avoiding problems associated with extraction at different temperatures and pressures. The trace metals are extracted with an ion-exchange resin (Chelex-100), or samples are acidified for direct activation analysis.

Samples have been collected from the Skagit River and its estuary, Washington. The river, which is relatively clean, has its headwaters in an extensive area of ridges and peaks in the Cascade Range. These samples are being analyzed for dissolved and particulate trace metals. For the dissolved samples, the metals are extracted by Chelex-100, followed by analyses on an atomic absorption spectrophotometer with a graphite furnace; activation analysis is used for particulate samples. After the concentrations have been determined, the speciation of the trace metals will be identified and the adsorption/desorption of trace metals on suspended matter will be studied.

To understand the surface chemistry of hydrous iron oxide, laboratory experiments have been designed to give quantitative data that can be used to evaluate the effectiveness of adsorption as a removal mechanism. The relative importance of adsorption on iron oxide versus manganese oxide in the marine environment can then be evaluated. Laboratory studies of the effect of the kinetics of oxidation of manganous manganese on the stoichiometry and mineralogy of manganese oxides and of the kinetics of oxidation of ferrous iron in seawater are planned.

Samples from the deep equatorial Pacific and from Narrows Inlet, British Columbia, have also been analyzed for dissolved and particulate trace metals. Subsequently, samples from Puget Sound, the continental shelf, and deep water will be available for analysis. (Murray)

### B. Diagenesis and Diffusive Exchange between Sediments and Overlying Water

The influence of the diagenesis of organic matter in marine sediments on the chemical composition of seawater is poorly understood. Because there is a large ratio of particle mass and surface area to solution volume in marine sediments, the chemical composition of pore waters should be a

sensitive indicator of the reactions of organic matter with the pore water. Theoretical models have been developed for describing the distribution of nutrients in pore fluids, but few field data are available for comparison. There is evidence that many sediments are oxygen deficient, and the diagenesis of organic matter on the continental shelf and slope may be a prime contributor to the establishment of the oxygen minima in the oceans and to the fluxes balancing the concentration of oxygen in the atmosphere.

To test some of these ideas, pore water samples will be obtained with the *in situ* sampler described above. Analytical techniques have been developed for analyzing microsamples for pH, alkalinity, and sulfide. We are currently developing techniques for determining  $\text{SO}_4^{=}$ ,  $\text{PO}_4^{=}$ ,  $\text{NH}_3$ ,  $\text{NO}_3^-$ , and  $\text{NO}_2^-$ . Pore waters of sediments from Narrows Inlet, British Columbia, show extremely high sulfide and alkalinity values. Additional samples will be obtained in Puget Sound during the winter, from the continental shelf in March, and the open ocean (San Diego to Valparaiso, Chile) in November. This sampling program will cover the entire range of marine sediments with different amounts of oxygen depletion. (Murray)

### *C. A Multidisciplinary Eastern Tropical Experiment*

An experimental program (METREX) is being designed to evaluate the relative effects of horizontal and vertical diffusion and of *in situ* biological-biochemical processes on the formation, maintenance, and decay of the highly developed oxygen minimum zone off Mexico and Central America. To simplify the analysis we plan to carry out the observations in the Lagrangian mode, i.e., an element of water will be tagged and followed with neutrally buoyant floats, parachute drogues, or both. One ship, the *T. G. Thompson*, will stay near the tagged element and make detailed and frequent observations of such variables as primary productivity, nitrate reductase activity, and the electron transport activity of the major populations at different trophic levels (bacteria, phytoplankton, net-zooplankton, and mesopelagic fish), while the vertical migrations of these organisms are monitored sonically. Chemical variables to be measured will include salinity, dissolved oxygen, nitrate, nitrite, ammonia, and phosphate. It is hoped that the observations can include continuous profiles of temperature, salinity (conductivity), and dissolved oxygen. To establish the density and motion fields governing the diffusion processes that alter each center of mass, measurements of vertical shears will be included.

A second ship will sail a geometric pattern around the *Thompson*, occupying hydrographic stations to establish the dynamic topography and the field of chemical variables. It will be positioned by radar contact with the *Thompson* which is equipped with Magnavox Satellite Navigation. Through daily transfer of chemical samples, all samples will be analyzed by the same personnel so that identical methods will be used, thus eliminating one source of error.

Theoretical bases for the program have been determined and the practical details of the shipboard observations are now being developed. (J. Anderson, Richards; A. Okubo, State University of New York, Stony Brook)

## D. Enzyme Activities and Environmental Factors

### 1. Nitrate reductase

Regulation of nitrate reductase (NR) activity by light. We have found that the induction of NR by light and its repression by darkness can be accomplished in 30 minutes. High light intensity represses nitrate reductase activity in the phytoplankton off Cape Blanc, Africa; experimental results from light experiments reveal an optimum at the 30% light level. The cyclic behavior of NR activity in the phytoplankton off Cape Blanc in 1974 resembled that observed in the same region in 1971, but contrasted markedly with the noncyclic behavior observed in the *Gonyaulax*-dominated populations off Baja, California. (Blasco, Packard)

Regulation of nitrate reductase activity by nitrate concentrations. The  $K_m$  of nitrate reductase for intracellular  $\text{NO}_3^-$  in the phytoplankton in the upwelling area off Cape Blanc is half the value observed in the plankton populations off the Baja, California upwelling area, which is dominated by *Gonyaulax*. The ratio of  $\text{NO}_3^-$  to  $\text{NH}_4^+$  in seawater appears to be more important than the absolute concentration of  $\text{NO}_3^-$  in determining the specific activity of nitrate reductase. (Blasco, Packard)

Inhibition of nitrate reductase activity. Inhibition of nitrate reductase activity by ammonium appears to be a universal phenomenon in all phytoplankton populations. It has been observed in the upwelling region off Cape Blanc in 1971 and 1974; in the upwelling waters off Baja California; and in polluted waters of the Saronikos Gulf, Greece. The observations suggest that: 1) Ammonium inhibition is important in the nitrogen assimilation process when the  $\text{NH}_4^+$  concentration exceeds  $0.15 \mu\text{g-at NH}_4^+$  per liter of seawater; 2) The specific activity of nitrate reductase can be used both as an index of the nutritional state of the phytoplankton and as an index of nekton and zooplankton excretion in phytoplankton nutrition. Values of NR/chl that exceed 20 suggest dependence on  $\text{NO}_3^-$ ; values less than 19 suggest dependence on  $\text{NH}_4^+$  and a nutritional coupling to ammonia excreting heterotrophs. (Blasco, Packard)

Relationship between nitrate reductase activity and nitrate uptake. This relationship is close to 1:1 in phytoplankton assemblages from upwelled waters. Off Baja California, the ratio between the two parameters was 0.92. This ratio is lower than the 1.5 to 2.5 range found in cultures. Close coupling between nitrate reductase activity and nitrate uptake is suggested by the parallel response of the two parameters to perturbations in the light and nutrient field. (Blasco, Packard)

### 2. Electron transport system

Significance of the activity of ETS as a bioindex of plankton metabolism in upwelling areas. A comparison of four upwelling ecosystems shows that both the phytoplankton and zooplankton above 50 m heterotrophically consume 31% of the carbon photosynthetically fixed by the phytoplankton. ETS activity in nanoplankton samples is an index of phytoplankton metabolism rather than zooplankton or bacteria metabolism. This conclusion is drawn from the close correlations between ETS activity and chlorophyll-*a* and between ETS activity and  $^{14}\text{C}$ -uptake.

Experiments on shipboard cultures of natural assemblages of phytoplankton show the existence of a diel ETS cycle that is in phase with the nitrate reductase cycle.

ETS activity and nitrate uptake in nanoplankton appear to be uncoupled. Plots of ETS versus nitrate reductase activity and nitrate uptake show no correlation. (Abrahamson, Wold [Packard])

Pressure studies. Laboratory studies on four local species of zooplankton have shown that the pressure effect on ETS activity is quite small when compared to the temperature effect. The effect of 500 atm of pressure at deep-sea *in situ* temperatures (1-7°C) is generally less than the effect of a 1°C temperature change. The results of a field study conducted on mixed populations of zooplankton from the eastern tropical North Pacific Ocean are in agreement; they indicate that the ETS activity at 2-3°C and 265 atm was not significantly ( $\pm 20\%$ ) different from activity at 1 atm for both surface (0-200 m) and deep (1000-2000 m) samples. As a practical matter, we conclude from these data that an appropriate correction factor for pressure effects on ETS activity of zooplankton collected from depths less than 2500 m would be negligible ( $< 10\%$ ).

We are currently studying the effect of pressure on ETS activity in bacteria. Experiments using the modified ETS assay (see XIII B) indicate that pressure may have a significantly greater effect on bacterial activity than it does on zooplankton activity. More definitive conclusions await further development of methods. (King, Packard)

Relationship to bacterial denitrification. We suspect that the ETS activity maximum associated with the oxygen minimum is not indicative of a zone of elevated biological activity, but is merely due to a change in the respiratory system, i.e., a shift from aerobic respiration to denitrification as a response to low oxygen concentrations. To test this hypothesis the changes in ETS activity that take place when a bacterial culture is shifted from aerobiosis to anaerobiosis have been measured. A pilot study on a steady-state, log-phase, chemostat culture of a marine bacterium indicates that ETS/R values for aerobic growth are similar to those in our batch culture experiments. More importantly, however, when the culture was shifted from aerobic to anaerobic growth, on a per cell basis, the ETS activity increased by a factor of 2.5, roughly the increase observed in the oxygen minimum zone of the Costa Rica Dome. (Devol, Packard)

#### *E. Large-scale Chemical Oceanographic Processes*

Relationships between large-scale circulation features, biologically mediated processes, and marine nutrient distributions are the subject of these studies. Current research is concentrated on denitrification in the eastern tropical Pacific Ocean, nutrient budgets for the Arctic Ocean, and nutrient fractionation between the oceans.

Papers dealing with the importance of horizontal processes in the denitrification zone of the eastern tropical North Pacific Ocean and with the possible importance of the Bering Strait exchange in nutrient fractionation between the oceans are in preparation and papers dealing with the dissolved silicon budget of the Arctic Ocean and with a possible relationship between increased marine denitrification and phosphorite deposition have been completed. (Codispoti)

#### *F. Reaction-Diffusion systems*

Periodic and steady-state characteristics of the vertical distributions of nonconservative properties can in some instances be modeled as coupled reaction-diffusion systems. This approach is being used to investigate the distributions of oxygen, nitrate, and nitrite in an oxygen minimum zone and the chlorophyll-phaeopigment distributions in the photic zone. In the first case, the important reactions associated with nitrate respiration are coupled to distributions of the properties with modified Michaelis-Menton kinetics. In the second case, the phaeopigment distribution is coupled to the chlorophyll distribution and a photochemical degradation rate. Initial analysis seems to indicate that photochemical degradation is responsible for a characteristic displacement of the phaeopigment peak below the chlorophyll peak. (J. Anderson, Richards)

## XVII. Marine Geochemical Studies

The main objective is to understand the chemical reactions that bottom and suspended sediments undergo in the marine environment. These studies include the mode of formation of manganese nodules, the effects of submarine volcanism on the chemical and mineralogical composition of marine sediments, the role of solid phases and organic ligands in controlling the distribution of trace metals and other chemicals in the ocean, the relationship of hydrocarbons in sediments to processes in the overlying water, and the role of mineralogical species in controlling the magnetic properties of the sediments.

### *A. Manganese Nodules*

The chemical composition of manganese nodules is being determined for comparison with the mineralogy of the manganese phases. Elements of particular interest are the rare earth elements and several of the transition metals. Manganese crusts, present on pillow basalts that have been dredged from a depth of 500 to 4000 m, are also being analyzed to evaluate the dependence of composition and mineralogy of the nodules on water depth (pressure) and composition of the encrusted basalt. (Piper and students)

The composition of several cores from the northeastern Pacific is being measured to ascertain the effect of the recent change in climatic conditions and sea level upon the rate of accumulation of iron, manganese, and associated elements within the sediments. (Piper)

Studies of ferromanganese nodules which led to four publications on thermomagnetic behavior of manganese nodules, magnetism and magnetic reversals in ferromanganese nodules, mossbauer and electron spin resonance spectroscopy of marine and fresh water manganese nodules have been completed. (Carpenter and students)

### *B. Geochemical Cycle of Arsenic in the Puget Sound Region*

A study of the biogeochemical cycling of arsenic, begun by E. A. Crecelius, is being continued. The natural distribution of arsenic in sediments, waters, and organisms of the area is modified by a large copper smelter near Tacoma, Washington, which releases large amounts of arsenic to the air and also directly to Puget Sound surface waters. Both arsenic rich dust and arsenic rich rain have been detected at least 30 miles downwind of the 600 foot stack of this smelter. A significant amount of the arsenic dissolves, some of which accumulates in the sediments. Budgets of arsenic fluxes into and out of Lake Washington and Puget Sound clearly show the importance of the discharges from the smelter. Analyses for arsenite, arsenate, and two methylated forms of arsenic in waters, sediments, and organisms of the area are under way. Identification of the forms of metals such as arsenic and mercury is important because the biological effects of the forms are variable. (Peterson, Engblom [Carpenter])

### *C. Geochemical Behavior of Mercury in Bellingham Bay*

Present mercury studies are concentrated in Bellingham Bay, in northern Puget Sound, where an estimated 4.5-9 kg of inorganic mercury were discharged

daily between 1965 and 1970 from a mercury cell chlor-alkali plant. The response of the Bellingham Bay system, especially the sediments, since the high discharge of mercury was stopped in 1970, has been of special interest. In sediments which are generally oxidizing and which had initial mercury concentrations of 2-10 ppm in 1970 the mercury is decreasing with a "half-life" of about 1.3 years--a surprisingly fast rate. Studies now in progress seek to determine the chemical forms in which the mercury migrates from the sediments to the overlying seawater. (Bothner, Carpenter)

#### *D. Lead-210 and Polonium-210*

Investigations of lead-210 and polonium-210 in sediments offshore of the Columbia River are under way, with the dual aims of learning more about these two natural radioisotopes in the sea and determining accumulation rates of Columbia River derived solids on the continental shelf and slope over the past 100 years. The lead-210 technique has also provided sedimentation rates over the last 100 years in Lake Washington and Puget Sound to date the time when man's discharges of arsenic, mercury, and oil began to appear in the sediments. The sorption/desorption behavior of these two isotopes and arsenic with suspended matter is also being studied. (Carpenter and students)

#### *E. Hydrocarbons in Lake Washington*

Studies of hydrocarbon distributions in waters, sediments, and organisms of Lake Washington are being performed as part of the determination of a budget of hydrocarbon fluxes in the lake. Forty times more hydrocarbons are found in surface sediments of the lake than at depth in cores from sediment layers deposited before man began influencing the distribution. Gas chromatographic characterizations show clearly that the increase is due to petroleum type hydrocarbons; storm sewer run-off has been shown to be an important source of these molecules. (Wakeham [Carpenter])

### XVIII. Chemical Studies of Marine Environments

These studies are designed to elucidate the chemistry of specific marine environments. In the past we have investigated the accumulation of the products of organic decomposition in anoxic marine systems; the solubility of iron sulfide and the distribution of trace metals in sulfide-bearing marine environments; and the distribution of particulate manganese in the ocean and specifically at the  $O_2$ - $H_2S$  interface in sulfide-bearing basins and fjords.

#### *A. Polychlorinated Hydrocarbons in Eutrophic and Oligotrophic Waters*

Uptake of polychlorinated hydrocarbons by phytoplankton and zooplankton in eutrophic and oligotrophic marine ecosystems is being investigated. These studies involve determination of kinetics, synergistic effects, and effects on mixed phytoplankton populations. Field sampling to measure chlorinated hydrocarbon concentrations in natural systems is being carried out with the objective of predicting the integrated transport within the ecosystem. (Pavlou)

#### *B. Oxygen-Deficient Environments*

Our continuing investigations of the processes producing oxygen-deficient conditions in silled estuaries have been shifted in emphasis from Saanich Inlet to the Jervis-Sechelt-Narrows (J-S-N) inlet system, British Columbia. The seasonal variations in the J-S-N system are being investigated with a series of cruises throughout the year. Hydrographic and chemical properties and biochemical rates of change are being measured in the water column and sediments to assess the seasonal distributions, rates of change of some nonconservative properties, and the importance of diffusion from the sediments.

Preliminary results indicate that Narrows and Sechelt inlets are flushed by dense water from Jervis Inlet every year. Narrows Inlet may flush more often. During quiet periods in Narrows Inlet respiration consumes the oxygen in the Bottom Water and nitrate respiration begins. The basin is flushed before all the nitrate is consumed and sulfate reduction begins.

It is hoped these measurements and knowledge of the volume and frequency of flushing in the J-S-N system can be used to model the seasonal variations in the chemical properties of the inlets. The long range goal is to understand how physical and biological processes compete to control the distributions of nonconservative properties in estuaries. We eventually hope to nondimensionalize the important processes into a scheme with which a variety of estuaries can be classified as to their resistance to becoming anoxic. (Smethie [Richards])

## XIX. Biome Studies and Marine Ecosystems Analysis

This program is designed to advance the field of marine ecology through coordinated, in depth, interdisciplinary investigations of specific marine ecosystems. From the viewpoint of this program the marine ecosystems are conceived, in an extension of the classical trophic level concept, as multi-component systems with transfer processes which relate to the components. The key to understanding the dynamics of these systems is the understanding of the spatial and temporal distributions of the components and the rates at which the transfer processes operate.

### A. Biome Studies

#### 1. Phytoplankton kinetics

The diatoms *Skeletonema costatum*, *Chaetoceros debilis*, and *Thalassiosira gravida* were grown in ammonium- or silicate-limited chemostats. At steady state, changes in cellular chemical composition and cell morphology were documented. The kinetics of ammonium and silicate uptake were studied by spike addition (perturbation) experiments. The change in the uptake rate of a nonlimiting nutrient, such as phosphate, was also followed during the perturbation experiment.

A mathematical model for silicate uptake of diatoms has been developed. It is based on the observations derived from perturbation experiments; the short-term uptake rate response to a spike addition of the limiting nutrient was found to consist of three distinct segments, a surge in the uptake rate ( $V_s$ ), an internally controlled uptake rate ( $V_i$ ), and an externally controlled rate of uptake ( $V_e$ ). A similar mathematical model for nitrogen is now being developed. (Dugdale, Harrison)

#### 2. Functional groups of phytoplankton

Work is under way to examine the role of uptake and growth parameters in interspecies competition in fluctuating and in near-steady-state environments. These parameters serve as input to mathematical models whose output will be compared with results of laboratory competition experiments.

Preliminary results on  $\text{NH}_3$ -limited cultures of *Skeletonema costatum* and *Thalassiosira gravida* have shown that cell reproduction cycles and morbidity effects observed in the laboratory can be used to generate successional phytoplankton distributions as a model output. In contrast, half saturation constants for growth and maximal growth rates as model inputs predict dominance only of *Skeletonema costatum* in all near-steady-state environments.

Objective analysis has been applied to the observed distribution of phytoplankton off Peru, Baja California, and the Attic peninsula to determine empirical groups of phytoplankton. Simulation models of competing functional groups of phytoplankton have been constructed for prediction of the distribution of these groups in oligotrophic and eutrophic environments with additional consideration of sampling error. (Walsh, Dugdale)

### 3. Variability of lower trophic levels of the New York Bight

A study has been initiated to consider the source of nutrient input to the boreal ecosystem of the New York Bight with examination of mixing processes at the shelf break. An assessment of the short-term (days) environmental variability of the nutrients, phytoplankton, and zooplankton south of Long Island is also under way to consider the impact of possible offshore nuclear power plants. A comparison of the composition of functional groups of phytoplankton in the New York Bight, Long Island Sound, Saronikos Gulf, and the eastern boundary currents off Peru, Baja California, and Northwest Africa is being conducted to analyze the functional role of red tide dinoflagellates within marine ecosystems. An analysis of the relevant frequency scales of events within these ecosystems is in progress with an attempt to apply the Nyquist Sampling theorem to field studies of biological variables. (Walsh)

### 4. Saronikos systems project

Studies of the regions of sea that are poor from lack of nutrient supply to the euphotic zone are being carried out from time to time to provide a more complete spectrum of conditions for our nutrient process research.

Research on transition processes as oligotrophic Mediterranean waters is transformed to eutrophic waters through the addition of municipal wastes has been undertaken jointly with the Greek Institute of Oceanography and Fishing Research. Monthly cruises have been made for two years and data analysis is under way. (Dugdale)

### *B. Coastal Upwelling Ecosystems Analysis*

The CUEA program, sponsored by IDOE, is based upon a systems approach to the study of biological production in upwelling regions. Within the physical and biological subdivisions, principal investigators from eight universities are engaged in component projects. JOINT-I, the first integrated major field exercise, was carried out off the northwest coast of Africa in February-June 1974. American, French, Spanish, Polish, Mauritanian, and East German research vessels participated. An NCAR aircraft, based in Nouadhibou, made sea surface temperature and a suite of meteorological measurements. JOINT-II is planned to take place in 1976-77 in Peru for a period of about 18 months. The program is carried out in the Department of Oceanography by eleven faculty members, with the assistance of several professional staff members and graduate students.

### 1. Statistical studies

The objective of finding diagnostic statistics which measure ecologically important properties of the nutrient and phytoplankton fields is taking two independent approaches. The first approach is basically empirical and involves the use of a number of statistics as descriptors of multivariate properties of the data sets. These statistics are designed to investigate the joint behavior of variables in large data sets. Hundreds of simulations of data collected from hypothetical models of nutrient/phytoplankton fields have been run and are used as the basis for interpretation of results from the real world. These techniques have the advantage that they do not depend upon assumptions regarding the nature of the probability distributions from which the data are drawn. The second approach, which is receiving major emphasis, is to analyze the time series by spectral, cross-spectral, auto- and cross-correlation

techniques in an effort to determine whether dominant scales of patchiness characterize upwelling areas.

Thus far, three measures of ecologically significant change in the nutrient-phytoplankton fields have been investigated:

1. The hyperspace distance. All measured environmental parameters (temperature, chlorophyll, nutrients, etc.) define a vector space. Any point can be the origin. At any other point which has different environmental parameters, the length of the vector joining the two points will indicate the degree of difference of the environments.
2. Interval correlations. A cruise track is broken up into intervals. Within an interval, if the environment is changing, the changes in many pairs of variables will be highly correlated. If all possible correlations are computed, and the mean square taken, it can be considered another index of change in an interval. The smaller the index, the more homogeneous the interval.
3. Multiplied variable surfaces. Measured parameters are interpolated onto all points on a rectangular grid encompassing a cruise track to produce a three-dimensional representation of the results. For speciation studies, the values of all the parameters associated with each grid point (after appropriate scaling) are multiplied and a new surface whose smoothness or roughness is indicative of the ocean homogeneity is generated.

Another investigation involves time-resolved correlations between nutrient field parameters. Data from a single cruise track provide estimates of the correlation, for example, between chlorophyll and silicate on a particular day. But estimates of the correlation between the chlorophyll today and the silicate three days ago are also of interest because the nutrients at some prior time affect the amount of chlorophyll present. Such time-resolved correlations are difficult to estimate on different days, since the ship frequently follows a different track each day. However, they can be interpolated from the interpolated grids, since at each grid point a history of measurements is available.

The application of multivariate time-series methods to data from coastal upwelling areas is also being investigated. Much of this work concentrates on the development of coherence estimates with known statistical properties so that significance tests can be developed. The results from the multivariate time-series model seldom provide much improvement over a Markov process model. However, the large volume of JOINT-I time-series data will be run to obtain standard spectral and correlation estimates of the field parameters. The changes in the structure and patchiness of the nutrient phytoplankton field will be analyzed and presented three dimensionally and spectrally for the entire experiment. (Kelley)

## 2. Kinetics of nutrient uptake

Using the  $^{15}\text{N}$  method, the uptake of nitrate and ammonium was studied in the Northwest Africa Upwelling System on the JOINT-I expedition. The major finding was a strong correlation between wind strength and the maximal uptake rates of both nitrate and ammonium; strong winds were correlated with the lower uptake

rates and low winds with the higher rates. Deep mixing induced by strong winds resulted in well mixed populations of phytoplankton with similar and low potential maximum uptake rates, presumably the result of the low average radiation levels. High maximal uptake rates could be induced experimentally by holding water samples for 24 hours in deck incubators prior to initiating the  $^{15}\text{N}$  measurements.

Using perturbation techniques developed in the chemostat laboratory, the uptake of phosphate, nitrate, ammonium, and silicate was studied; populations were first concentrated using reverse-flow filtration. According to criteria developed in work with nutrient-limited cultures, the phytoplankton in the JOINT-I study area exhibited the symptoms of nitrogen-limited populations, apparently the result of low effective light levels induced by turbulent mixing. Uptake rates measured with this technique correspond very well with those made with the  $^{15}\text{N}$  method. (Dugdale)

### 3. Regeneration and excretion

During the JOINT-I cruise off the coast of Northwest Africa, excretion rates of zooplankton and principal nekton species were obtained. Excretion and respiration rates of zooplankton were measured on four size fractions and on individual specimens of the largest-size class. Excretion measurements were collected for several semidemersal nekton species.

Preliminary excretion results combined with zooplankton and nekton biomass data gathered by other components in CUEA indicate that rates of nutrient regeneration vary with the location in the Northwest Africa Upwelling System. Small zooplankton contribute a larger fraction of the zooplankton biomass inshore than offshore but regeneration at inshore stations and offshore stations is nearly identical as a result of the higher biomass of larger organisms at offshore stations. The regeneration of nutrients by nekton is largest at inshore locations because of the relatively high biomass in that area. When the amount of nitrogen excreted by zooplankton and nekton is compared to ammonia uptake by phytoplankton, the inshore area is more dependent on regenerated nitrogen than the offshore. (Whitledge)

### 4. Systems model of an upwelling ecosystem

Numerical models of the circulation, nutrient uptake, grazing, regeneration, diurnal migration, and photosynthetic processes in x, y, z, and t domains of an upwelling ecosystem have been constructed for analysis of the trophodynamics of the eastern boundary currents off Peru, Baja California, and Northwest Africa. The varying terminal yield of these ecosystems has been related to the intermittency of seasonal wind stress, the shelf width, and the prey patchiness parameterized in grazing thresholds. Questions of carbon and nitrogen coupling, of size and grazing efficiency, of multiple nutrient regulation, and of loci of detrital distribution and remineralization have arisen from the above analysis; field experiments have been planned to resolve these hypotheses. Time-dependent models of the seasonal flux of nitrogen within the Southern Ocean and the Sargasso Sea also suggest that oligotrophic systems may be more efficient in consideration of  $Q_{10}$  inverse size-metabolism relationships and differential impact of patchiness as a function of predator size. (Walsh)

## XX. Plankton Production

A material part of the efforts of biological oceanographers, in the field and the laboratory, is directed at primary and secondary production of the plankton. The goals are to describe, explain, and predict the rate of production of organic matter in space and time, and the resulting distributions and abundance of organisms. The methods used for the plankton are quite different from those employed on the sea bed, because the same plankton populations cannot be regularly revisited. Other studies of plankton production are summarized in Section XIX.

A comprehensive effort concerns the area off the coast of Washington, with emphasis on the continental shelf; these studies will be correlated with investigations on circulation, sediment transport, and geochemistry of the same area.

### A. Coastal Waters off Washington and Oregon

#### 1. Quantitative evaluation of 1961-3 data

A comprehensive quantitative study on the seasonal distribution and annual variability of phytoplankton, zooplankton, and related environmental variables in the Columbia River plume and beyond has now been completed. It is based on a large amount of data for hydrography, nutrient chemistry, phytoplankton productivity and biomass, and zooplankton obtained from 1961 to 1963. The data were evaluated primarily in suitably averaged form. Several aspects of this study have been reported in previous summaries of research activities in this department, but it is worth noting that we now realize that the average spring primary production was slightly higher in 1963 than in 1961 and not the reverse, as had been thought previously.

A simulation model for phytoplankton biomass changes from March to May 1963 at an "average station" each in the plume of the Columbia River and in the oceanic environment was formulated with special emphasis on zooplankton grazing. The grazing influence of the large overwintering copepods *Calanus cristatus*, *C. pacificus*, and *C. plumchrus* was studied relative to each other and to smaller copepods. Algal concentrations were simulated at two depths corresponding to the 50% and 10% levels of the surface illumination. The coefficients of the model were derived from the averaged field data obtained in 1963, from laboratory observations, and from the literature. Algal growth rates were estimated from simulated *in situ* experiments on primary productivity. Rates of phytoplankton respiration and sinking were taken from the literature. Nutrient limitation was not included specifically but the maximum amount of photosynthetically assimilated carbon was limited by the total available inorganic nitrogen in the photic zone. Grazing mortality of phytoplankton, which was considered as a function of available food and of the biomass of copepods, was prescribed by sixteen equations: five, corresponding to copepodite stages (I to V), for each of three species of large copepods, and one for a category "small copepods." Various papers on ingestion rates of copepods were utilized to obtain grazing coefficients.

A reasonable similarity between the observed and simulated chlorophyll concentrations was noted. It was also found that, in both the plume and ambient

seawater, grazing by small copepods must be very important in controlling levels of phytoplankton productivity and biomass. Among the large copepods, grazing by *C. pacificus* in the plume and by *C. plumchrus* in ambient seawater seems to be significant. A single grazing scheme for all zooplankton was found to be inadequate. The results emphasize the need for better estimates of ingestion rates of small copepods and for reevaluating the influence of *C. plumchrus* and *C. cristatus* in controlling and maximally utilizing primary productivity. Limitations of the model including the coefficients of vertical eddy diffusivity and the parameters involving metabolism and growth of copepods were noted when the total planktonic ecosystem, including inorganic nitrogen, phytoplankton, and herbivorous zooplankton, was examined. (Hameedi [Banse])

## 2. Subsurface chlorophyll maximum

The subsurface chlorophyll maximum found off the shelf of Washington and Oregon continues to attract our strong interest. During 1975, three cruises are planned to investigate the processes leading to its formation and maintenance.

Our previous investigations have shown that during the summer months a subsurface maximum of chlorophyll is a major biological feature of the North Pacific Ocean at intermediate latitudes. Beyond the continental slope off the coast of Washington and Oregon, the layer is found typically, at 55-65 m, between the seasonal pycnocline and the permanent halocline. Chlorophyll concentrations may be 3 to 10 times as high as in the layers above. Although the maximum may be well below the depth where 1% of the surface light is found (this depth traditionally being taken to be the bottom of the euphotic zone), up to one half of the daily primary production per square meter is due to the phytoplankton associated with the subsurface maximum layer. A large part of the observed increase of pigment may be due to *in situ* growth of the phytoplankton but other mechanisms such as increase in cellular chlorophyll and sinking of cells from above must be considered. Although estimates have shown up to a 10-fold increase in chlorophyll, only about a three- to four-fold increase in cell carbon occurs within the layer. Previous studies on phytoplankton in the area of the Columbia River effluent overlooked the chlorophyll maximum, which, however, cannot be neglected in assessing the possible pathways of organic matter in the region.

In the water above the continental shelf, contiguous to the area of upwelling off Oregon, another quite local subsurface maximum of chlorophyll occurs which may, in part, be caused by advection of surface water seaward along the sloping isopycnals. (Anderson)

Phytoplankton enumeration. About 125 phytoplankton samples have been examined microscopically using the Utermöhl technique. The samples were primarily from stations occupied off Oregon in 1968 and described earlier by Anderson in reference to the horizontal patchiness involved in the chlorophyll maximum layer. Species were identified and enumerated, and cell dimensions were measured for calculation of cell carbon. Comparisons are being made between the phytoplankton populations of inshore and offshore stations and between surface and chlorophyll maximum layers at appropriate stations.

In general, a three- to four-fold increase in both cell number and cell carbon was found in the chlorophyll maximum layer compared with surface offshore waters. Species found at depth but not at the surface did not contribute significantly to either total cell number or cell carbon. Dinoflagellates, microflagellates, and coccolithophorids were as abundant as diatoms. At the offshore

stations, microflagellates usually accounted for about 50-60% of the cell numbers, but only about 10% of the biomass at all depths. In surface waters dinoflagellates made up 20-25% of the numbers and 55-70% of the biomass, while diatoms made up 15-20% of both numbers and biomass. However, in the chlorophyll maximum layer, dinoflagellates and diatoms sporadically alternated in biomass dominance. At some stations large cells of *Rhizosolenia alata* f. *inermis*, *Thalassionema nitzschioides*, and *Coscinodiscus* spp. were much more prevalent than at other stations and, hence, diatoms contributed up to 30-40% of the cell number and 40-75% of the biomass. When the above-mentioned species were not prevalent, the proportion of diatoms to dinoflagellates was similar to that of the surface layer. However, dinoflagellates were always important contributors to the biomass (about 20%) of the chlorophyll maximum layer.

At stations over the shelf, diatoms comprised 65-75% of the total cell number at all depths; dinoflagellates accounted for about 10%; and coccolithophorids and microflagellates each made up 5-10% of the population. In terms of cell carbon, however, diatoms contributed 55-70% of the biomass, dinoflagellates 15-30%, and coccolithophorids and microflagellates about 3-5% each. Silicoflagellates at times comprised up to 15% of the biomass, although they represent only 1-3% of the cell numbers. (Postel [Anderson])

Compensation light intensity. The high rates of photosynthesis measured in and below the deep chlorophyll maximum show that the 1% of surface light depth is not a reliable indicator of the depth of the euphotic zone, and commonly quoted values for compensation light intensity are probably too high for oceanic phytoplankton in the Northeast Pacific. However, it may be argued that the algae in the subsurface chlorophyll layer are highly shade adapted (as we have observed ourselves) and may not be characteristic of oceanic phytoplankton in general. Also, our earlier *in situ* measurements of photosynthesis were made over the daylight period (sunrise to sunset) and therefore did not allow for loss of  $^{14}\text{C}$ -tagged organic matter by respiration at night. Therefore, we occupied a station to the north of the area where the subsurface maximum is found and made *in situ* measurements both from sunrise to sunset and for 24 hours to depths below the 0.1% surface light level. The  $^{14}\text{C}$  uptake values from 24-hour incubations were slightly less than those from daylight incubation but were nevertheless measurable to below the 0.1% light depth.

It appears from our measurements that compensation depths are deeper than earlier estimates for large areas of the ocean, including areas where subsurface maxima of phytoplankton are absent. We are aware that the depth at which  $^{14}\text{C}$  uptake reaches zero is somewhat below the 24-hour compensation depth because the method is likely to yield a measurement between net and gross production. We also recognize that the bottom of the photic zone is likely to be tied to a range of absolute light intensities rather than to percentages of surface light. Therefore, in a hypothetical situation with seasonally constant extinction coefficients, the compensation depth would be at shallower absolute depths in winter than in summer, as well as at shallower light depths (i.e., depth expressed as percentage of surface light). The field work is continuing using a quanta meter which is sensitive to levels of light below the 0.1% depth in summer time. (Anderson)

Nitrogen uptake. Field measurements of inorganic nitrogen uptake by phytoplankton are available from four summer and autumn cruises in 1972 and 1973. Nitrate, nitrite, and ammonia uptake were measured using  $^{15}\text{N}$ . Urea uptake was not determined. As time and equipment permitted,  $V_{\text{max}}$  and  $K_s$  were estimated.

Although each of the cruises had stations in areas where subsurface chlorophyll maxima are generally found, the layers were not as well developed as have been described in recent papers.

Maximum nitrogen uptake rates usually occur at the 50-25% light depths (generally about 25 m). There does not appear to be a pronounced increase in uptake of nitrate relative to ammonia with increasing depth as found by others, for example, off the coast of Mexico. For our region, which has nutrient-poor surface waters, nitrate uptake accounted for 20-25% of total inorganic nitrogen requirement; nitrite represented only 5-10%; and ammonia supplied 70-75% at all depths. Thus it seems that most of the productivity in the area is "regenerated" (using  $\text{NH}_4$ ) rather than "new" (using  $\text{NO}_3$ ) in the sense of Dugdale and Goering. Further work is needed in areas where the chlorophyll maximum is well developed.

Estimates of the C:N ratio from  $^{14}\text{C}$  and  $^{15}\text{N}$  uptake yielded values much below the theoretically expected 6.6 (the textbook ratio given for phytoplankton cellular composition) in subarctic waters of the North Pacific; the value usually was less than 2.5. On the other hand, ratios of 13-25 were common for transition and subtropical waters. To assess the effects of varying degrees of N- or Si-limitation on C:N assimilation ratios over 48 hours, two experiments using chemostat cultures of *Skeletonema costatum* were performed. In one experiment, the ratios were generally less than 3.0, and in the other the ratios were usually greater than 4.0 with all degrees of nutrient limitation.

The investigation of nitrogen uptake was continued on a cruise off the Washington coast in July 1974. Uptake of  $^{15}\text{N}$ -labelled nitrate, ammonia, and urea were measured concurrently at three stations using simulated *in situ* techniques. At four stations,  $V_{\text{max}}$  and  $K_s$  for one or another of these forms of nitrogen were estimated for the populations at the 100% and 3% light depths. The analyses of samples have not yet been completed. (Postel [Anderson])

Phytoplankton-zooplankton relationships. One of the major uncertainties in assessing the impact of grazing activity of zooplankton on natural phytoplankton is unpredictable heterogeneity in the spatial distribution of both phytoplankton and zooplankton. Usually both are spatially heterogeneous in three dimensions, and the use of average concentrations of plants and herbivores to calculate grazing losses can give large errors. A subsurface chlorophyll maximum represents a reduction in spatial heterogeneity of plants to predominantly two dimensions. Further, if herbivorous zooplankton is aggregated within a temporally persistent layer of phytoplankton (e.g., Anderson, Frost, and Peterson, 1972), then study of the dynamic relationships between plants and herbivores is significantly simplified. We are making field investigations of the grazing activity of zooplankton by taking advantage of the existence of the seasonal subsurface chlorophyll maximum.

We plan to determine if relatively mobile, herbivorous planktonic animals actively aggregate and remain in the layer of the chlorophyll maximum. Our investigations to date indicate that they probably do, but our earlier techniques of sampling zooplankton with horizontally or obliquely towed nets may sometimes have obscured spatial relationships between plants and herbivores; thus, the greatest concentrations of herbivores was not always found in the chlorophyll maximum layer. To reduce the effects of horizontal patchiness on such observations, the vertical distribution of zooplankton is examined by sampling with large (1 m diameter) vertically towed closing nets. Zooplankton sampling is preceded and followed by pump casts for vertical profiles of chlorophyll.

Vertical sampling of chlorophyll and zooplankton is done several times (both day and night) at a station. The hypothesis that herbivorous zooplankton actively aggregates in subsurface chlorophyll maxima is accepted if, in a series of vertical profiles, the correlation between vertical distributions of plants and herbivores is strongest when the chlorophyll maximum is best developed. The zooplankton samples will provide us also with estimates of the biomass of herbivorous species.

Two shipboard methods are under development for estimating the grazing rates of zooplankton within the chlorophyll maximum. The methods give different types of information on grazing, but together may yield a comprehensive picture of how zooplankton utilizes natural phytoplankton. One method involves placing representative herbivores into large batch cultures of unfiltered seawater from the chlorophyll maximum layer. The grazing rates of herbivores are measured by periodically obtaining size spectra of suspended particles with a Coulter particle counter. Control batch cultures, without grazers, are always used. These experiments can only give results on the total volume of particulate matter ingested by zooplankton. It remains to demonstrate what fraction of that ingested volume represents phytoplankton.

A second, indirect, method of estimating *in situ* grazing rates of zooplankton depends on our frequent observation that herbivorous copepods from the chlorophyll maximum have full guts, i.e., were probably actively feeding at the time of capture. If these animals were placed in water from the chlorophyll maximum and allowed to graze for a short period of time, then their rate of production of fecal pellets would be directly related to their feeding rate. Fecal pellet production can be expressed, for example, as dry weight, carbon, or nitrogen. By applying an average value for assimilation efficiency one can estimate the ingestion rate. The results will be related to the concentration of food by measuring the amount of particulate organic carbon and chlorophyll contained in the seawater used in the experiments. Experiments of this type were carried out by a former colleague (V. W. Kaczynski) who also developed a method for estimating efficiencies from elemental ratios (C:N) in food and fecal pellets. Obviously, aspects of both experimental methods for estimating *in situ* grazing rates require some laboratory development before being applied in field work. (Frost)

### 3. Microzooplankton

The microzooplankton obtained off the Oregon coast, generally from 0, 20, 50, and 100 m depths, in summer 1973 are being investigated. Approximately 40 pump-delivered samples, passed by a 20  $\mu$  net but retained on a 20  $\mu$  screen, have been examined. Tintinnid ciliates are the most dominant microzooplankters in terms of cell numbers; 30 species have been identified. From surface samples it is possible to distinguish three basic tintinnid species assemblages: neritic, Columbia River plume, and open ocean. The greatest cell numbers were found in the station closest to shore, but few other quantitative generalizations can be made regarding surface samples. Cell specimen numbers usually decreased with depth. No significant correlations could be found between cell numbers and chlorophyll *a* or primary productivity values obtained from water bottle samples at the same time. Indications are that tintinnids may be more highly correlated with physical parameters such as salinity and temperature. Sedimented whole-water samples yielded larger cell numbers than net samples.

In summer 1974, one-liter microzooplankton samples were obtained on a section extending from the Washington coast. Generally 4 (but sometimes 8) depths were sampled, depending on the position of the chlorophyll maximum. In addition, several pump-delivered net collections were obtained from the surface. This work has not been completed; however, preliminary evidence suggests that the ciliate maximum coincides with the depth of the chlorophyll maximum.

Isolation and culture of tintinnid ciliates is continuing. (Chester[Anderson])

#### 4. Plant pigments

The determination of plant pigments in the sea and the use of these measurements as indices of biological processes continues. A research program has been designed towards a "pigment budget" of the water column. Efforts are concentrated on chlorophyll *a* and its metabolic products. Primary reasons for this are: 1) Energy utilized in the photosynthetic process must pass through the chl *a* molecule, and 2) techniques available to measure chl *a* and related pigments are more advanced and precise than methods that could be used for the measurement of other plant pigments. Also, the other pigments are not studied at present either because their ecological significance is uncertain; or, if they are potentially useful for interpretation of ecological phenomena, the information is more readily obtained in another manner.

Naturally occurring chlorophyll *a*-like pigments include chlorophyllide *a*, phaeophytin *a*, and phaeophorbide *a*. The first member, chlorophyllide *a*, can be found in the surface layers only. Traces of phaeophytin *a* can be found throughout the water column. By and large, the most abundant species is phaeophorbide *a* which is present throughout the water column and in the underlying sediments. All three, and the parent chlorophyll *a*, can be separated and identified by a combination of chromatography and either spectrophotometry or spectrofluorometry. Quantification of any one member of the group is to some degree uncertain since techniques in use do not differentiate between chlorophyll and chlorophyllide or between phaeophytin and phaeophorbide but do distinguish between the two groups. Evidence from chromatography indicates that chlorophyll and phaeophorbide are relatively much more abundant than chlorophyllide and phaeophytin within the water column.

Production of the different species appears to be variable. Chlorophyllide is a precursor in the normal synthesis of chlorophyll but its presence in pigment samples may at times be an artifact of the technique, especially if extraction is carried out over an extended period of time, since chlorophyllase does not seem to be inactivated in acetone. Neither phaeophytin or phaeophorbide can be produced by placing algal cultures in the dark. Chlorophyll *a*, however, is readily degraded to phaeophorbide by passage through the gut of a herbivore. Phaeophytin appears in the pseudofeces of mollusks but not in fecal pellets. Presumably, it is produced from the parent chlorophyll if the algal cell is killed in a specific manner.

Because the sole source of phaeophorbide in the ocean appears to be herbivore grazing, its distribution should be relatable to phytoplankton-herbivore interaction. Complications arise from sinks for phaeophorbide produced in the water column. Phaeophorbide is light-labile; consequently, fecal material produced and retained in the upper portions of the euphotic zone will be photo-oxidized. Larger fecal pellets, however, settle rapidly and are dispersed throughout the water column making sampling more difficult.

The present sampling is conducted in conjunction with zooplankton studies off the coasts of Washington and Oregon. Concurrent laboratory studies are described in section XX E. (Lorenzen)

#### 5. Phytoplankton dynamics

A numerical study of primary production is being conducted in conjunction with the biological and physical investigations being carried out off the Washington coast beyond the continental shelf. The primary aim is to identify and describe the major physical and biological processes governing seasonal phytoplankton production and distribution. A numerical model is being developed of the offshore phytoplankton distribution in time and depth, i.e., one-dimensional in space. The model attributes time variations of the algal (chlorophyll) concentration to vertical turbulent diffusion, phytoplankton sinking, gross productivity, respiration, and zooplankton grazing.

Each of these processes is regarded as a submodel within the chlorophyll distribution model. The functional form to be used in these submodels is poorly understood and not all of the necessary measurements are available. For instance, the vertical diffusion coefficient is both time- and depth-dependent and will have to be supplied to the model as an independent input. In past studies, algal sinking has been variously assumed to be constant, to vary with the density of the seawater, and to depend on the physiological state of the phytoplankton. Gross productivity is dependent on light intensity and on the ambient nutrient concentrations. The actual functional form of light and nutrient dependence, as well as the interrelationship in the dependencies, has been subject to different interpretations in the literature. Although loss to zooplankton grazing is usually taken to be governed by an Ivlev-type equation, the dependence of the constants both on zooplankton species and on cell size is only now being determined with appropriate precision.

This particular phase of the offshore study is designed to test the sensitivity of the chlorophyll distribution to different formulations in the various process submodels and to changes in the "measured" independent variables. At the present stage of the work, the independent variables include the diffusion coefficient, light intensity, nutrient concentrations, and zooplankton density. A reasonable initial distribution of phytoplankton will be imposed on the model from available data and the changes of the phytoplankton population will be simulated over a season as the external conditions (independent variables) evolve. By changing each of the submodels individually and by changing the evaluation of the independent variables separately, we expect to be able to discriminate between those processes and variables which strongly influence the results and those which are less important. We also expect to be able to identify those processes that need to be further studied in the laboratory and in the field. (Lam, Winter)

#### 6. Surf-zone diatoms

Along the coast of the Olympic Peninsula extending northward from the Columbia River mouth to Point Grenville (a distance of approximately 75 miles), extensive blooms of diatoms occur in the surf zone throughout the year, reaching their greatest magnitude during the autumn, winter, and spring months. These diatom populations constitute the major food of razor clams which support an important fishery, especially for sports fishermen. During the period

1920-1930 when preliminary investigations were made, the centric diatom species *Aulacodiscus kittoni* was the dominant species in the blooms, but it has since disappeared from this area. Subsequently, *Chaetoceros armatum* appears to have predominated. The smaller, colonial pennate diatom *Asterionella socialis* has been recognized as the second most important species for the past 50 years, and the centric diatom *Biddulphia aurita* has been the third but minor constituent in the blooms. Light, temperature, salinity, and nutrient requirements of the two dominant forms have been determined.

The regional and temporal occurrences of the blooms and of the environmental factors which may influence them have been studied for three years emphasizing the area near Copalis Beach. The environmental conditions prevailing during late autumn, winter, and early spring do not vary much from year to year, whereas the conditions in the late spring, summer, and early autumn may vary greatly, depending on the magnitude and duration of the northerly winds and the extent of river discharge. Conditions in the surf between late spring and early autumn have been different for each of the three years of the study so that it is not clear what a "typical" yearly pattern of events might be. It is clear, however, that during the periods of absence of nitrate (6 months during 1971, less in the other years) ammonia is the principal source of nitrogen for the bloom; it is usually around 1  $\mu\text{g-at/l}$  but occasionally reaches values several times as high. Phosphate and silicate are always present in ample concentrations.

A study of the nitrate reductase (NR) activity of *C. armatum* at Copalis Beach over a period of 18 months has been completed. Variations of enzyme activity depended on the season and the time of day. General seasonal trends in NR activity were correlated with nitrate concentrations in the surf zone, but several factors may limit the activity of the enzyme. Enzyme inhibition due to the presence of ammonium occurred on several occasions throughout the study period. This phenomenon for the most part masked any pattern of diel periodicity in NR activity that might have been expected in the natural environment. Cultures of *C. armatum* and *Asterionella socialis* were also studied. A diel fluctuation in NR activity corresponding to the pattern shown in natural phytoplankton by other authors was exhibited in *C. armatum* under a light-dark regime of 8L-16D and a light intensity of 4000 lux.

*C. armatum* has been studied experimentally in the field. The species undergoes a diel periodicity of buoyancy such that the cells are dispersed through the water column at night and rise to the surface each morning. The cells become buoyant before daybreak and tend to disperse in late afternoon so that buoyancy is not light-induced (Lewin and Hruby, 1972). Although there is periodicity in division, the resulting periodic change of chain length could not be correlated with changes in buoyancy. It could be shown experimentally, however, that even in daytime, the diatoms are not positively buoyant as such, as they sink in buckets. They float only after air bubbles are provided, be it by the surf action or by bubbling compressed air through the bucket. The mechanism does not work during nighttime.

The first collection in spring 1974 has not yielded conspicuous concentrations of the surf-zone diatoms. We are engaged in further monitoring the surf zone, coupled with physiological studies in the field and the laboratory. Problems to be emphasized include the question of the source of the ammonia supply in the field, and of the biochemical changes of the cells or cell surfaces which relate to floating. (Lewin)

*B. Dynamics of Spring Phytoplankton Blooms in Puget Sound*

The long-range objective of this investigation is to identify the environmental and physiological factors which govern biological production in the central basin of Puget Sound. To this end, we have developed a quantitative model of the interrelationship between circulation and phytoplankton production in the basin and applied it to historical data of hydrographic variables, nutrient salts, rates of primary production, and phytoplankton and zooplankton concentrations. The data were taken at a midchannel station in the central basin off Seattle during the spring months of 1966 and 1967 on an almost daily basis, following biweekly collections from September 1963 through 1965.

Phytoplankton growth in the central basin is dominated by a number of intense blooms beginning in late April or early May and recurring throughout the summer months. Daily carbon uptake rates often reach several grams per square meter, but chlorophyll *a* concentrations do not exceed 15 to 29 mg/m<sup>3</sup>. Near the surface, nitrate may decline to limiting levels but these episodes are infrequent and short-lived. The net-collected zooplankton amounts to only about 10 mg C/m<sup>3</sup>, and it was inferred that nutrient regeneration from ammonium excretion plays a minor role in primary production at this station.

Previously, an approximate mathematical model was developed of gravitational circulation in the central basin (Winter, 1972). The analysis described turbulent diffusion and the time-mean velocity fields as continuous functions of depth and distance down-inlet. Input data to the hydrodynamic model are freshwater run-off intensity, salinity at depth, and the tidal range. The numerical model of phytoplankton growth represents concentration as a continuous function of space and time, and ascribes changes in phytoplankton density to variations of specific photosynthetic and respiratory activity, sinking, grazing by herbivores, and to mixing and advection. All biological coefficients are drawn from the literature except for the averaged and seasonally adjusted rate of light-saturated photosynthesis with its corresponding value of optimum light intensity. Input data supplied to the phytoplankton model on a daily basis are as follows: turbulent mixing coefficient, (calculated) velocity and density fields, incident light intensity, nitrate and zooplankton concentrations, and the average chlorophyll concentration at 30 m, which is approximately the greatest depth of the euphotic zone. Some of the special features of the model are as follows: Underwater light flux is computed from the observed incident light intensity and from the extinction coefficient which is dependent upon the phytoplankton density and the concentration of terrigenous sediment as estimated from salinity. The Michaelis-Menten expression, modified by the inclusion of a time lag of 72 hours, is used to model nitrate limitation. The near-surface specific respiration rate of the algae is decreased exponentially with depth from the surface to the 1% light depth, below which depth net production over 24 hours is assumed to be zero.

Comparison of the computed and observed results indicates that the model reproduces most of the general features of the phytoplankton population dynamics at the station during 75 and 35 days in the spring of 1966 and 1967, respectively. Several numerical experiments with only one factor being varied in each computer run demonstrate, for example, that a decrease in respiration rate with depth is required to reproduce the average chlorophyll concentration within the water column as well as its vertical distribution in the euphotic zone. The effect of grazing by the net-collected zooplankton is shown to be minor,

even though the specific grazing rate used is high. However, the grazing effect is marked when an estimate of the mass of the small zooplankton is incorporated. Changing the sinking rate from 0.5 m/day to zero has little effect on the integrated chlorophyll concentration above the Secchi depth but a sinking rate of 3 m/day removes most of the algae from this zone.

It is concluded that the very late onset of spring phytoplankton blooms and the subsequent, frequent and rapid changes in concentration within the central basin of Puget Sound are not explainable in terms of the critical depth concept. Rather, phytoplankton growth is limited by a combination of factors including vertical advection and turbulence, modulation of the under-water light intensity from self-shading and other particulates, sinking of algal cells, and rapid horizontal advection of the population from the area on occasions of sustained southerly winds. It is also concluded that the functions and parameters traditionally employed to describe phytoplankton metabolism are only marginally adequate for short time-scale models. The results from this project should be of general applicability to other temperate fjords because of the largely conventional choice of the biological functions.

It is anticipated that these studies will be continued as new data become available from the 1975 studies (see Section XXVI M), particularly in regard to analysis of phytoplankton dynamics during the low river-flow period in August-September. (Winter, Banse, Anderson)

#### *C. Models of Annual Phosphate-Phytoplankton Cycles in Lake Washington*

Several numerical models have been developed recently to study seasonal variations of algal growth and nutrient concentrations in lakes. These include compartment or "box" models as well as vertically integrated models of the distribution of various substances related to water quality. This project was undertaken to assess the feasibility of constructing a different sort of model of deep stratified lakes where the biological, physical, and chemical properties are continuous functions of space and time. In particular, a "demonstration" model has been constructed of the annual cycles of phosphate and algal concentrations in Lake Washington, Seattle, which was chosen for modeling since adequate data for verification of a coarse time resolution analysis of primary production and nutrient cycling are available.

Despite several critical idealizations, calculations with the model reproduce many features of the historical data acquired in the lake during eutrophic years, thereby demonstrating the feasibility of the approach. However, the demonstration model was oversimplified in at least two important respects: the impact of zooplankton grazing was neglected and turbulent mixing in the vertical was described by an eddy-diffusion coefficient which decayed exponentially with depth from the surface to the vicinity of the thermocline. We are presently giving high priority to a re-examination of this last idealization. Specifically, we are using procedures similar to those developed by Sundaram and co-workers to relate the vertical turbulent diffusivity in Lake Washington to the thermal structure of the lake via the local Richardson number. When this task is completed, we can then examine in a self-consistent way the influence of turbulent diffusion and other environmental variables on the annual cycles of nutrients and algal populations in a deep temperate lake such as Lake Washington. (Winter)

#### *D. Stability of Steady-State Depth Distributions of Phytoplankton*

A certain class of steady-state marine phytoplankton distributions has been reviewed and examined for stability. The results indicate that a traditional conservation equation, which describes the distribution of marine phytoplankton in space and time, admits to a class of steady-state solutions dependent only on depth. In mathematical terms, the solutions correspond to unique values of certain dimensionless parameters  $\gamma_1$ ,  $\gamma_2$ , and  $\lambda$  that depend upon environmental and physiological factors. More specifically, parameters  $\gamma_1$  and  $\gamma_2$  are proportional to average net specific production rates within and below the euphotic zone, respectively, and  $\lambda$  is proportional to an effective algal cell sinking rate. The proportionality factors involve the euphotic zone depth and the depth-mean turbulent diffusivity. The steady-state solutions are shown to be neutrally stable to perturbations of the dependent variable. From the biological point of view, this implies that the concept of a time-mean depth distribution of the algae in the open sea is valid only as long as special relationships are satisfied amongst the average turbulent mixing intensity, the effective algal sinking speed, and the time-mean net specific primary production rates in and below the photic zone. It has also been demonstrated that the inclusion of lateral diffusion in the traditional conservation equation for the algal distribution has a stabilizing effect, but does not necessarily eliminate horizontal patchiness after long intervals of time.

In reality, short-time changes (over periods of hours or days) occur both in the physical variables and in the specific production rates, and the plankton community responds appropriately within the same time interval. Over a longer time scale, suppose that an algal community has achieved a steady-state distribution corresponding to appropriate values of  $\gamma_1$ ,  $\gamma_2$ , and  $\lambda$ ; if a sustained change occurs in one or more of the several environmental variables so that a new triplet ( $\gamma_1$ ,  $\gamma_2$ ,  $\lambda$ ) obtains, then a perturbation of the steady state will inevitably result. According to the analysis performed in this project, the perturbation so induced will move the community distribution to a new steady state only if the new triplet lies on a neutral curve in the  $\lambda$ - $\gamma_1$  plane; if it does not, the algal concentration will tend everywhere to zero or grow without bound. In nature, unlimited growth never occurs because nonlinear self-shading and nutrient exhaustion inevitably will curtail and reduce the production at all depths. It is concluded that a proper understanding of algal population dynamics, of spatial distribution characteristics, and of other important aspects of phytoplankton in the marine environment probably requires both time and space-dependent analyses. (Criminale, Winter)

#### *E. Release and Uptake of Dissolved Organic Carbon by Phytoplankton*

Production and consumption of dissolved organic carbon (DOC) by natural phytoplankton were studied in areas of the oceanic and coastal Northeast Pacific Ocean and in Puget Sound. Release of DOC relative to total productivity was significantly related to light intensity, chlorophyll  $a$ , and nutrient concentration. The accumulations of excreted DOC in seawater during day and night were measured; the patterns observed were explained by interaction between rates of release and heterotrophic activity. Michaelis-Menten-type kinetic parameters for the uptake of phytoplankton-derived DOC concentration of the ambient seawater. One to 23% of phytoplankton-derived DOC was immediately re-utilized via heterotrophic uptake, 60-65% was removed through adsorption on particulate matter, and 12-39% entered the free DOC pool of the seawater. These fractions may reflect the molecular weight of the DOC - only the low

molecular weight fraction may be readily available to the phytoplankton. Species composition of the algae is also believed to be important. (Hartmann [Anderson])

#### *F. Phytoplankton Studies in the Subarctic North Pacific Ocean*

Environmental and biological data collected on 37 merchant vessel crossings between the Pacific Northwest and Japan during the first six months of 1969 through 1972, and data from research vessel cruises in 1969, 1971, and 1972 have been utilized in studying the distribution of insolation, surface water temperature, mixed layer depth, plant nutrients, chlorophyll plant biomass, phytoplankton, and microzooplankton. On the basis of statistical analyses of the phytoplankton distribution, the Subarctic Pacific can be divided into five regions: Japan Coastal/Transition, Western Gyre, Aleutian Coastal, Eastern Gyre, and North American Coastal/Transition. The geographical limits of these regions correspond to the limits of the upper zone domains described earlier by physical oceanographers. This regional separation of the Subarctic Pacific is also supported by differences between regions in the seasonal distribution of plant nutrients, surface water temperature, and mixed layer depth, as well as in the timing of the onset of the spring phytoplankton bloom. The three coastal regions show increased production in March with a subsequent decrease in nutrient concentrations, while production remains at low levels in the gyre areas until May. With the exception of the areas within 20 miles of the shore, nutrients are not reduced to limiting levels.

The dominant phytoplankton group in oceanic waters in terms of cell numbers consisted of the small (2-7  $\mu\text{m}$  in length)  $\mu$ -flagellates, which regularly accounted for from 50% to over 80% of total cells present. In terms of biomass this group made up from 13% to over 50% of total phytoplankton biomass. Large concentrations of microzooplankton (< 200  $\mu\text{m}$ ), especially species of tintinnid ciliates which ranged from 300 to 2500 cells/liter, were found in the same samples. Since these animals may be expected to utilize phytoplankton cells which are < 10  $\mu\text{m}$  in size, the importance of tintinnids in the transfer of energy to higher levels of the food chain is strongly suggested.

Evaluation of the ability of certain mathematical models to predict the timing and level of the spring phytoplankton bloom indicates that a modification of the model by Steele and Menzel reproduces the major features of changes in phytoplankton and productivity; however, confidence intervals are large. Inputs to the model are insolation, extinction coefficient, average chlorophyll in the mixed layer, and mixed layer depth. A multiple regression analysis of the data indicates that the most important parameters for estimation of primary productivity in the region are insolation and mixed layer depth, and that nutrient concentration is not an important consideration. These results support the observation of others that the Subarctic Pacific is primarily a light-limited regime. (Munson [Anderson])

#### *G. Role of the Bacterioplankton in the Tropical Pacific Ocean*

In a series of papers concerned with the concentration and rates of production of heterotrophic bacteria in the tropical Pacific Ocean, Sorokin suggested that the role of the bacterioplankton often exceeds severalfold that determined for the phytoplankton. The organic matter required for this production was believed to be advected in dissolved form, at depth, from higher latitudes; the low temperature at the high latitudes and at depth prevents rapid degradation

of the dissolved organic matter. Thus, the warm-water sphere serves as the major sink of the dissolved organic carbon accumulated in the deep sea (and hence, in the entire ocean, for all practical purposes).

By comparing the rates of bacterial production measured by Sorokin with the consequences for the geographic distribution of dissolved organic carbon in the Pacific tropical surface waters, it can be shown that the average production of organic matter by bacterioplankton must be one order of magnitude smaller than that of the phytoplankton in the same water. Sorokin's experimental estimate for the bacterial production in the deep sea is too high by more than an order of magnitude. The conclusions are likely to hold for all oceans. Thus, the location of the major sink for the dissolved organic carbon reaching the deep sea is still unknown. (Banse)

#### H. N/P Ratios in the Photic Zone Water and the Plankton

The ratio of removal of nitrate and phosphate ions from seawater have been related to the elementary composition of the plankton since the discovery of the relatively constant ratio of changes of these ions by Redfield in the 1930's. It is being suggested here that there is no *a priori* reason to expect that the ratio of disappearance from seawater has to be correlated with the composition of the phytoplankton, or even with the total particulate matter. The ratio of disappearance of nitrate (and ammonium) and phosphate ions from the photic zone is the net result of *removal* into the various particulate pools (phytoplankton, zooplankton, and non-living particulate matter) and the pools of dissolved organic nitrogen and phosphorus, and *release* from any of these pools into the inorganic pools of the elements. Only some of the rates of these processes are correlated, e.g., grazing by zooplankton and excretion. Others are not correlated, e.g., rate of phytoplankton growth in nitrate-rich water and rate of the mineralization of the elements from the dissolved organic pool. The various rates do not happen to balance each other so that the ratio of disappearance of the ions from the water is similar to that of the composition of newly formed particulate matter, as can be shown by a reconsideration of the seminatural culture run in a large plastic sphere by the Nanaimo group in 1962. The atomic ratio of net removal was approximately 13.5:1, that of the newly formed particulate matter about 22:1. (Banse)

#### I. Feeding Ecology and Population Dynamics of Herbivorous Planktonic Copepods

This research program has the goal of contributing to our knowledge of factors controlling the distribution and abundance of the major planktonic herbivores in Puget Sound. Laboratory feeding experiments have yielded information on both tactics and strategy of feeding in the copepods *Calanus pacificus* and *Pseudocalanus* sp. In the adult stage *C. pacificus* is about ten times larger in weight than *Pseudocalanus* sp. and, although both copepods are filter feeders, they seem to be adapted to utilize different ranges of the particle size spectrum of phytoplankton. *C. pacificus* feeds most efficiently on larger food particles; in laboratory cultures individual specimens develop and grow fastest when fed large food particles; *Pseudocalanus* sp. specializes on small food particles. These results support our belief that the size composition of the phytoplankton is one of the dominant factors influencing feeding behavior and, ultimately, population growth of herbivorous copepods.

A field sampling study was carried out for one year in the main basin of Puget Sound near Seattle and in Dabob Bay, a deep tributary basin of Hood Canal. The purpose of this study was to determine trends in population size of *C. pacificus* and *Pseudocalanus* sp. and to relate the trends to environmental parameters. The two sites were chosen for comparison because there is a significant difference in the timing of the spring blooms of phytoplankton; the bloom occurs about 2 months earlier in Dabob Bay. Preliminary results of the field study indicate that in both basins *Pseudocalanus* sp. begins reproducing long before the spring bloom of phytoplankton while reproduction in *C. pacificus* is determined by the timing of the spring bloom. Seasonal variations in body size of the two species support this observation. These results are predictable from knowledge acquired in our laboratory experiments. (Frost and co-workers)

*J. Population Dynamics of a Pelagic Copepod in a Small Lagoon*

Members of the pelagic copepod genus *Acartia* are important components of coastal and estuarine zooplankton communities. By concentrating on a small well-defined population that can be revisited readily, it may be possible to generate information which will prove useful in understanding the dynamics of *Acartia* in areas which are less amenable to direct observation.

A population of *A. clausi*, semi-isolated in Jakle's Lagoon on San Juan Island, Washington, has been studied for a two-year period (1973-74). The focus of the study is the dynamical aspect of the population which is dependent, at any point in time, on the abundance of animals and the rates of fecundity, development, and mortality. Mortality estimates are obtained from laboratory-derived development rates and stage-abundance data from field samples collected through time. Secondary production will be estimated from laboratory growth rates and the calculated mortality schedule. The pattern of spatial distribution of life stages varies on a daily and seasonal cycle which may be influenced by population density and, therefore, by factors which affect the population parameters. (Landry [Frost])

## XXI. Benthic Production

The objectives of this program are the same as those of plankton production, i.e., to describe, explain, and predict the rate of production of organic matter in space and time, and the resulting distribution of abundance of organisms. Biological processes in the seawater on the continental shelf, with its plankton, cannot be understood without taking the interaction with the sea bed into account. Research in this field is not well advanced in the United States; however, it needs to be promoted not only for its intrinsic interest but because bottom organisms in many cases are more affected by, and therefore better indicators of, pollution than those of the plankton.

A. *Dynamics and Production of an Interstitial Harpacticoid Copepod*

Populations of interstitial harpacticoid copepods were sampled from three intertidal sand beaches in Puget Sound. Quantitative replicate core samples to a depth of 20 cm were taken at approximately weekly intervals for one year and temperature and sediment parameters were monitored. Preliminary results show that the copepods reach high densities during spring ( $10^5 - 10^6/\text{m}^2$ ), with lower levels prevailing during the rest of the year ( $10^3 - 10^5/\text{m}^2$ ). Approximately 10-20 species are present, depending upon beach location, sediment size, depth within the sand, and tidal elevation. Harpacticoids have been sampled from a depth of 45-50 cm at one beach.

A numerically dominant species, *Huntemannia jadensis*, is being analyzed in detail for its abundance, age structure, and reproductive state. It comprises from 10-50% of all harpacticoid specimens and appears to produce two generations per year. Growth rates at optimal food levels in the laboratory at 8, 12 and 15°C are temperature-dependent. Generation time is long compared with other copepods. Mortality is highest in the naupliar stages, both in laboratory cultures and in the field. Production will be estimated in terms of carbon-utilizing instantaneous growth parameters and biomass estimates. (Feller [English])

B. *Studies of Benthic Community Metabolism*

These investigations had the following objectives: 1) To study the oxygen consumption by the sea bed of the shelf and the continental terrace slope off Washington and Oregon, as well as on the deep-sea floor of the northern North Pacific Ocean; 2) to investigate the possibility of indirectly estimating the flux of organic matter to the bottom; 3) to adapt a method of measuring dehydrogenase activity to the measurement of anaerobic metabolism by sediment bacteria; 4) to compare the measurements of dehydrogenase activity with those of direct calorimetry; and 5) to compare the total metabolic heat release by the sediment column with the total metabolism estimated from oxygen uptake by intact cores.

Some of the objectives have been achieved. The measurements on undisturbed sediment cores of total oxygen uptake, residual oxygen consumption after poisoning, and respiration have been published and the implications discussed (Pamatmat, 1973). The goal of estimating the oxidizable flux of organic matter to the sea bed from a combination of field and laboratory experiments has not yet been realized. A modified method of estimating dehydrogenase activity in sediments was developed and applied to Lake Washington sediments. By calibrating this assay against direct microcalorimetry, it could be shown experimentally that

the oxygen consumption by the lake bottom does not represent the total metabolism of the sediment column because not all of the end products of anaerobic metabolism at depth reach the sediment surface and are oxidized there (Pamatmat and Baghwat, 1973).

These studies are continuing on the shelf off Washington, with the emphasis on the role of the sea bed as a sink of particulate organic matter and oxygen and a source of regenerated nutrient salts. Because our previous investigations stressed regional coverage, the focus will be on seasonal investigations of oxygen consumption and the study of special processes in shelf samples and laboratory models. Specifically, it is planned to measure onboard ship, preferably, three times a year the rates of oxygen consumption across the shelf, the rates of anaerobic metabolism in subsurface sediments, the rates of nutrient release from sediment cores, profiles of oxygen depth and redox potential in sediments, nutrient concentrations in the interstitial water, and the ATP concentrations in sediments (as a measure of biomass of small organisms), along with organic carbon, nitrogen, phosphorus, and grain size. In the laboratory, the relationship between nutrient release by shelf sediments will be studied under aerobic and anaerobic conditions, and related to the loss of organic carbon and nitrogen. (Pamatmat, Auburn University, Auburn, Alabama, and assistants in the Department of Oceanography.)

#### *C. Long-Term Stability of Subtidal Bottom Fauna in Puget Sound*

Rarely in comprehensive ecostudies, e.g., of fish production of an area, or in the ecosystem approach, can all relevant components be studied simultaneously. Instead, for many parameters, one has to rely on previous investigations in the same area. Basic to any extrapolation, however, is information on the natural variation with time and the possible causes. With few exceptions, subtidal benthic stations have not been revisited more than once so that little general knowledge exists about long-term stability of community structure (ranking of species by numbers or biomass), and almost nothing is known about variability of production rates, as distinct from observed changes of standing stock, of the benthos.

Puget Sound is one of the two or three marine (rather than estuarine) sites with published information on long-term stability of subtidal populations. We have intermittent records for some stations since 1963, where macrofauna (retained by a 1 mm screen) were sampled with the same gear; we also have made detailed studies of community structure, and, for shorter periods, of production of some of the dominant species.

Subsequently, three of the stations have been sampled biannually since May 1973 during the seasons when most species populations are composed of large specimens, and therefore the screen retains a considerable part of each population. As the environment at the sites is similar to the open shelf, information of a general nature is expected to result from a continuation of this project. Moreover, Puget Sound is the type locality for Sanders' Maritime Climate Boreal Community (in the context of the stability-time hypothesis), so that the data will be of general interest also for this reason.

The proposed five-year program will stress initially the dynamics of dominant species: variation of biomass and production estimates, and the possible relation of variations with, for example, presence or absence of competing species.

It is hoped that subsequently estimates of the production by the entire macrobenthos can be attempted and that crude limits of confidence, based on observed natural cycles or trends, can be established. (Nichols, U. S. Geological Survey, Menlo Park, California; Kisker)

## XXII. Biology of Marine Organisms

While being principally concerned with the temporal and spatial distributions of populations and the abundance of marine organisms, biological oceanography draws heavily on knowledge of the biology of marine organisms. Beyond this application, the biology of marine organisms is of intrinsic interest.

The inclusion of the research projects under this heading rather than under Biome Studies and Marine Ecosystems or Plankton and Benthic Production is somewhat arbitrary.

### A. *Growth and Nutrition of Unicellular Algae*

#### 1. Heterotrophic growth

Work on facultatively heterotrophic diatoms continues. Species which normally grow by photosynthesis in the light but which can also grow in the dark utilizing organic compounds as energy and carbon source have certain ecological advantages. Thus, the results of such laboratory studies have implications for various ecological measurements in the field. Previously, growth and metabolic behavior for diatom species which utilize sugars (glucose) and organic acids (lactate, succinate) have been investigated here. Currently, the emphasis is on those species that have the capability of multiplying in the dark by utilizing amino acids (predominantly glutamate) as substrates. Growth rates in the dark and in the light, rates of uptake of carbon compounds, and efficiency of utilization of compounds have been measured, and metabolic pathways determined. Three papers reporting the results on amino acid utilization are currently in preparation and a review chapter on heterotrophic nutrition of marine diatoms is being written (Lewin; J. Hellebust, University of Toronto).

#### 2. Role of boron

A second nutritional problem being investigated is the requirement for boron by marine diatoms and the role of this element in their physiology. The requirement for boron is absolute as diatoms cannot multiply in its absence, and the growth rate of the cells is affected when boron is present in low concentrations in the culture medium. Higher plants also have an absolute boron requirement, and although the exact role of boron has not been worked out, it appears to be important in the synthesis of RNA. A study has just been completed in which the content of carbohydrates, proteins, lipids, DNA, RNA, and phenolic compounds have been compared in boron-deficient and normal diatom cells. The cellular constituents most affected by boron deficiency were RNA and phenolic compounds, thereby showing that diatoms behave like higher plants in this respect. Studies on the role of boron are being continued (Lewin; Chen, Department of Chemistry).

#### 3. Availability of iron

The proportions of soluble and particulate iron in Puget Sound and Hood Canal were investigated as well as the changes in these fractions which occur after the seawater was placed in containers. A considerable amount of the soluble iron (6-8  $\mu\text{g/liter}$ ) is in the ferrous form, which was hitherto not realized. Upon enclosure in containers, the soluble iron disappears within a few

hours and goes either to the particulate fraction (in an unfiltered sample) or onto the walls of the container (in a filtered sample). Results of this study have been published. Studies of the iron requirements of various species of diatoms are being carried out in the laboratory. (Lewin; Chen, Department of Chemistry).

#### B. Light Adaptation of Marine Dinoflagellates

Recently, several dinoflagellate species have been isolated and specific problems concerning the culture medium and the behavior of the species in culture are being studied. The capability of both dinoflagellate and diatom species to utilize light of low intensity and to grow at high-light intensity is being investigated.

Specifically, *Ceratium pentagonum*, a marine dinoflagellate, was isolated from Puget Sound and grown in unialgal cultures. Its mode of light adaptation was determined from growth rates, cell size, and chlorophyll *a* and protein contents per cell. Light saturated growth rate at 13°C occurs at about 140 foot-candles of continuous light. A gradual increase in the chlorophyll *a* to protein ratio is observed at light intensities lower than 140 foot-candles, as well as a decrease in cell size and in protein content per cell.

Experiments are being performed on other dinoflagellate species to investigate further the ability of light adaptation of this group of marine primary producers. (Chan [Lewin])

#### C. Effects of UV Radiation on Phytoplankton Photosynthesis

The effects of UV radiation, both at ambient and elevated levels, on phytoplankton photosynthesis is being investigated. The region of the spectrum of special interest is light of wave lengths shorter than 320 nm. Naturally occurring sunlight striking the surface of the earth contains very little energy in this region and it is fair to say that energy at wave lengths shorter than 290 nm does not exist. This narrow band, 290-320 nm, corresponds to the ozone absorption band and it has been suggested that the concentration of ozone may be reduced as a result of high altitude aircraft flights, thereby increasing incident UV radiation levels on the surface of the earth.

Experiments on the photosynthetic uptake of  $^{14}\text{C}$  were conducted in either quartz or vycor glassware, which are transparent to UV while either pyrex or other normal laboratory glassware is not. Controls consisted of  $^{14}\text{C}$  uptake experiments in either quartz or vycor screened with a sheet of mylar which is opaque to radiation shorter than 320 nm. Experimental bottles were suspended in the water column and exposed to natural sunlight for 2 hours before and 2 hours after local apparent noon. In all cases an inhibitory effect was found when *in situ* levels exceeded 0.01%  $I_0$ . Inhibitory effects were at times quite large, reducing  $^{14}\text{C}$  uptake levels to 10-50% of the controls.

Light between 290-320 nm is not much more strongly attenuated by "pure" seawater than visible energy. On the other hand, naturally occurring suspended and dissolved materials do absorb UV radiation more rapidly than visible energy. As a result, in coastal, fairly turbid waters, UV is attenuated to 0.01%  $I_0$  in only a few meters or in an interval corresponding to the upper 1/3 of the euphotic zone. In oceanic waters, UV would be attenuated less rapidly although

more rapidly than visible light and the same level, 0.01%  $I_0$ , would be lower, approximately halfway down through the euphotic zone.

Experiments are continuing to examine further the effects of UV levels that are higher than those presently incident on the surface of the earth. (Lorenzen)

#### D. Cell Size and Rates of Metabolism of Unicellular Algae

Because the cell size of unicellular algae spans about as large a size range as that of extant mammals, one might expect size-dependence of physiological processes among algae as it is known for coldblooded and warmblooded animals. Some field observations have in fact been published showing that the specific rate of carbon uptake is higher for the small-size fraction of natural phytoplankton than it is for the larger one. Also, growth rate of algae cultured under uniform conditions has been demonstrated by others to be inversely related to cell size. It can be shown for four sets of data from the literature that the size-dependence of growth can also be quantified by the allometric formula of growth of comparative animal physiology,  $\text{growth (carbon [cell} \cdot \text{time}]^{-1})} = a (\text{cell carbon})^b$ , where  $b$  is smaller than unity. The algae, which were of widely different size, had been cultured under uniform conditions. Size-dependence of respiration is suggested from one of these data sets. Possibly, the size-dependence of growth and respiration is most marked when algae grow under optimal conditions. Growth efficiency ( $\text{growth [growth + respiration]}^{-1}$ ) is not size-dependent. It is postulated that gross photosynthesis as well as the underlying physiological processes must be size-dependent to the same degree as respiration in order to have growth efficiency independent of size. Cell size, expressed as carbon, is proposed as a scaling factor for comparative algal physiology. (Banse)

#### E. Chlorophyll Degradation by Herbivores

The degradation of chlorophyll to phaeophorbide takes place in the herbivore gut. This phenomenon may lead to a method of estimating grazing rates by the measurement of phaeophorbide in the water column. Knowledge of the amount of phaeophorbide produced as a result of the ingestion of a given amount of chlorophyll is necessary before estimates can be made. Grazing experiments were run in the laboratory, primarily with *Calanus* sp. as a grazer and *Coscinodiscus angustii* as a food source. The time course of the decrease in chlorophyll concentration and the increase in phaeophorbide concentration was followed. The percent conversion of chlorophyll to phaeophorbide was found to average 66% on a weight basis and 100% on a molar basis. Some chlorophyll was found in fecal pellets. The specific adsorption coefficient of phaeophorbide in 90% acetone at 667 nm was determined to be  $53.5(5\text{-cm})^{-1}$ , approximately the same as that of phaeophytin under the same conditions. This fact is important because previous studies have incorrectly identified chlorophyll degradation products as phaeophytin. The similarity of their specific adsorption coefficients allows the use of previously published equations for phaeophytin in the determination of phaeophorbide. (Shuman [Lorenzen])

#### F. Threshold Feeding Behavior in Planktonic Herbivores

Simulation models of the lower trophic levels in plankton communities usually specify a threshold feeding behavior for planktonic herbivores. Without a feeding threshold, the simulated phytoplankton population goes to extinction. The

evidence for a threshold feeding behavior in planktonic herbivores is equivocal and, further, there may be alternative ways to assure the persistence of phytoplankton under grazing stress, e.g., overdispersion of phytoplankton which would permit an escape in space from herbivores. A series of laboratory feeding experiments was designed specifically to determine the feeding behavior of a planktonic herbivore at very low food densities. Adult females of the copepod *Calanus pacificus* were fed on the diatom *Thalassiosira fluviatilis* at several densities of cells, all well below the critical concentration. As food concentration decreased, copepods filtered at a constant maximal rate until their ingestion rate fell below about 15% of the maximal hourly ration; then the copepods fed at a significantly depressed rate. The concentration of food at which this threshold feeding behavior occurs apparently depends on the size of the food particles. (Frost)

#### G. Laboratory Studies of Two Microzooplankton Species

Carbon turnover rates of the marine and brackish water rotifer *Brachionus plicatilis* and the large marine protozoan *Noctiluca miliaris* are being compared. The two species are planktonic herbivores of similar size which grow well on small flagellates.

Ingestion rates for *B. plicatilis* increase with increasing food concentration up to about 10 mg C/l, thereafter levelling out. Maximum ingestion rate for three flagellates (*Dunaliella tertiolecta*, *D. euchlora*, and *Isochrysis galbana*) is close to  $2.2 \times 10^{-5}$  mg C/hr-individual at 20°C. Ingestion rates increase with temperature within the range measured (15° to 25°C). Instantaneous growth rates of *B. plicatilis* increase with increasing food concentrations and temperatures. For *Noctiluca*, optimal doubling time is about 24 hours. Instantaneous growth rates increase with increasing food concentration and increasing temperature up to 20°C; growth is regarded at 25°C. As in *B. plicatilis*, *I. galbana* as food gives highest growth rates, *D. tertiolecta* gives slightly lower rates, and *D. euchlora* gives very low rates (doubling time of a week or more). Respiration rates for *Noctiluca* cells in log phase grown on maximum food is  $1.56 \times 10^{-6}$  ml O<sub>2</sub>/hr-individual at 20°C and  $1.28 \times 10^{-6}$  ml O<sub>2</sub>/hr-individual at 15°C. (Dewey [Banse])

#### H. Carbon and Nitrogen Budgets for a Carnivorous Amphipod

Specimens of the marine amphipod *Calliopius laevisculus* were raised in the laboratory at 8°, 12°, and 15°C from time of birth until the end of their life cycle. The first 2 or 3 instars were fed phytoplankton and the remaining 9-10 instars were fed adult *Calanus pacificus* females.

The purpose of the project, which is presently nearing completion, was to determine the effects of temperature and animal size on the parameters of the budget equation

$$C = P + M + F + L + T$$

where C is ingestion, P is production (growth and reproduction), M is metabolism, F is defecation, L is leakage of organic carbon or nitrogen, and T is molting. The measurement of all parameters allows for an internal check of the budget because no value is determined by difference. All parameters for various size classes and at 3 temperatures were measured in terms of both carbon and nitrogen.

In approximate terms, a carbon budget for a *C. laeviusculus* which has attained instar 12 would be as follows:

30-40% of all the food killed by this individual during its life span was returned immediately to the water in the form of microscopic particles and soluble material leaked from the prey while it was being eaten (Dagg, 1974).

60-70% of the killed food was ingested:

10% was voided as particulate carbon in the form of fecal pellets.

15% was partitioned into production.

10% was returned to the water as soluble organic carbon in the form of leakage products.

4% was returned to the water as particulate carbon in the form of molts.

The remainder was returned to the water in the form of respiratory CO<sub>2</sub>.

Thus, although 15% of the ingested food was partitioned into production, an equal amount of particulate carbon was produced in the form of feces and molts, and a somewhat smaller amount was produced as soluble organic carbon via excretion. Trophic analysis is typically approached in terms of production, yet these other forms of organic carbon are quantitatively greater than production. They can be of importance as food and surfaces and should not be ignored. (Dagg [Banse])

#### *I. Effect of Environmental Parameters on Zooplankton Growth*

The effects of temperature, food concentration, and food size on the laboratory growth rate of two planktonic copepods *Calanus pacificus* and *Pseudocalanus* sp. are being investigated. The former species was raised from copepodite I to adult at 8°, 12°, and 15.5°, and food concentrations of 50, 170, 350, and 700 µg C/l, using as a food source the diatoms *Thalassiosira* sp., 9 µm in diameter, *Th. excentrica*, 20 µm and 30 µm in diameter, and *Th. angstii*, 64 µm and 35 µm (at 12°C only) in diameter. *Pseudocalanus* sp. was raised at the same temperatures and at food concentrations of 30, 50, 170, and 350 µg C/l, using as the source of food *Th. excentrica*, 18 µm and 30 µm (at 12°C only) in diameter.

Preliminary analysis of the data shows strong interactions among all the parameters. The effect of food size on growth seems to be far more important than the effect of temperature. However, growth at high food concentrations for food sizes greater than about 30 µm in diameter seems to be independent of food size. Thus, a concentration of 7000 µg C/l of small cells (9 µm) produces slower growth rates than a concentration of 50 µg C/l of large cells (over 30 µm).

Animal body size is also correlated with food size, food concentration, and temperature. Low temperature, high food concentration, and large food size produce large body size (in terms of weight); however, this effect is manifest only in the last stages of development.

C/N ratios in *Calanus* remain relatively constant under the different treatments; only at low temperature, high food concentration, and large food size are they slightly higher, probably due to the excessive accumulation of oil under these experimental conditions. (Vidal [Frost])

### J. Chemical Communication in Two Marine Planktonic Copepods

The sparsely distributed planktonic animals in the ocean seem to be remarkably successful at finding mates during sexual reproduction. In natural populations of planktonic copepods unfertilized females are rare. Experiments were carried out to determine if intraspecific mating encounters in the marine planktonic copepods *Calanus pacificus* and *Pseudocalanus* sp. are controlled by a pheromone produced by the adult females. A characteristic swimming behavior, unique to adult males, is elicited by exposing the males to water which previously contained recently molted adult females. It was shown, by direct measurement and by autoradiographic techniques, that males take up dissolved organic matter, presumably a pheromone, from recently molted females which were labelled with  $^{14}\text{C}$ . The major receptors for pheromones are on the male antennules and appear to be the aesthetes.

Experiments in progress are determining if adult males of *C. pacificus* respond to the crustacean molting hormone ecdysterone. (Griffiths [Frost])

### K. Distribution of Zooplankton in Tidal Channels

Zooplankton is distributed more or less passively by horizontal currents, but each species usually occupies a characteristic depth which might be actively altered in response to physical and biological factors. Strong tidal mixing and disturbances in the vertical distribution of zooplankton would have an effect on the behavior and horizontal distribution.

Samples were collected in September and October 1974 from the NOAA ship *McArthur* to investigate the response of the zooplankton to mixing in tidal channels. These two cruises were an extension of ongoing physical oceanographic surveys, particularly on tides and tidal currents, in San Juan Island channels. Day/night series of samples were collected south of San Juan Island and in East Sound, areas of minimal tidal mixing. The principal series was collected northeast of San Juan Island in a region of strong tidal mixing. Collections were made at consecutive maximum flood, slack water, and ebb for four tidal cycles (ca. 50 hours) on each cruise. Depths sampled, with a 60-cm vertically hauled closing net, were 200-75 m, 75-50 m, 50-25 m, 25-10 m, and 10-0 m.

The vertical distributions of zooplankton in the relatively unmixed and the strongly mixed areas will be compared. The degree to which different species are affected by mixing will be considered, as will the differential resumption, if any, of typical distributions during slack water. An attempt will be made to compare apparent mixing effects with the time rate of change of vertical water velocities. (Damkaer; Larrance, NOAA)

### L. Vertical Migration and Feeding Behavior of Mesopelagic Fish

Diel vertical migrations are a significant aspect of the biology of many mesopelagic fish. The causes of migratory behavior are elusive, but trophic interaction may be the dominant factor. To test whether vertical migrations of mesopelagic fish represent appetitive behavior towards aggregations of zooplankton prey, a field investigation is being made of the feeding behavior of small mesopelagic fish from both migratory and nonmigratory sonic scattering layers. A new trawl was developed for this work; it

is an opening-closing trawl controlled and monitored electronically, and adapted to carry five separate nets; vertical tows were made with the trawl.

The first field study was made in August 1973 in the subarctic North Pacific Ocean near the Canadian Ocean Weather Station "Papa." Day and night vertical tows were made at 55-m depth intervals from the surface to 440 m. At station "Papa" there are only three abundant species of mesopelagic fish, all myctophids; two of the three species perform diel vertical migrations. Preliminary analysis of the gut contents of the fish shows that although they ingest a wide variety of prey species and sizes, they are inordinately fond of the small luminescent copepod *Metridia lucens*.

A second field study was made in July 1974 at 51°N 137°W. Complete day and night samples were collected as in the previous study, but sampling was concentrated in depth intervals known to be occupied by the dominant myctophid species. Fine-scale sampling indicates that the vertical distributions of two of the dominant species are closely correlated with observed migratory sonic-scattering layers. There appear to be both quantitative and qualitative differences in the fish and zooplankton communities between the 1973 and 1974 study areas. Preliminary analysis of the gut contents of the fish from the 1974 study area shows that euphausiids, the amphipod *Parathemisto pacifica*, and the copepod *Metridia lucens* are the dominant prey organisms. Analyses of the vertical distributions of the fish and their prey species are continuing. Differences in the diet of the three dominant species of myctophids may provide clues to the adaptive significance of diel vertical migration. (McCrone [Frost])

#### *M. Categories of Pleuston and Neuston*

For several decades, the term neuston referred to organisms associated with the surface film of the water and using the surface tension for physical support; those that were attached to or moving on its upper side were termed epineuston and on its lower side, hyponeuston. In the marine literature, during the last 10-15 years, the term hyponeuston has also been applied to organisms freely swimming in the upper 5-10 cm of the sea. The new meaning of the term hyponeuston is now widely used which indicates that there is a need for a shorthand term for this assemblage of organisms. Many among them exhibit adaptations in morphology, physiology, and behavior to the special conditions of this habitat.

In order to avoid confusion with the original term hyponeuston, the following definitions, which apply to both salt and fresh water habitats, are proposed:

**Pleuston:** Organisms specialized by morphology or behavior to live on or below, but close to, the surface.

**Exopleuston:** Pleustonic organisms partially emerged, floating on the surface by being lighter than water (e.g., *Lemna* spp., *Physalia* spp.).

**Endopleuston:** Pleustonic organisms living fully submerged and ordinarily not lighter than water (e.g., many species of *Pontellidae*).

**Neuston:** Organisms attached to or moving on the surface film of the water, thus deriving their principal means of support from the surface tension of the water.

Epineuston: Neustonic organisms living above the surface film (e.g., some Protista; Gerridae).

Hyponeuston: Neustonic organisms living below the surface film (e.g., some Protista).

Pleustal: The zone in which the pleuston lives: below the surface in the marine realm, the uppermost decimeter. (Banse)

### XXIII. Biogeography and Taxonomy

Biogeography deals with the distribution of organisms and is concerned not only with the phenomena at the present time but also with those of the past, thereby illuminating the origin and history of the fauna and flora. Biogeography, as well as most other aspects of biology, entails taxonomic work. The functions of taxonomy are threefold: identification, classification, and the study of species formation and of factors of evolution. Immediate objectives in biological oceanography, however, are often to solve pressing problems of identification in ecological or stratigraphic research.

#### A. Taxonomic Studies of Marine Pelagic Diatoms

Taxonomy of diatoms of the North Pacific is a poorly investigated field. Major taxonomic inquiry has been directed toward fossil species and neritic species. Oceanic species have been studied primarily from net samples, thereby neglecting small cells and culture methods and the scanning electron microscope (SEM) have not been applied to them.

In this study three oceanic species in the *Thalassiosira oestrupii* group have been isolated from the North Pacific, grown in culture, and observed with the SEM. All three have probably previously been called *Coscinodiscus eccentricus*. Variations within this group are being studied in cultures and in field samples. A new species of *Actinocyclus* which is closely related to *A. curvatulus* has also been isolated. The entire life cycle, which has unusual features, has been observed in culture. The classification of this species will depend on SEM observations of the pseudo-nodule. Two species in the *Coscinodiscus lineatus* group are being studied in culture. SEM observations will probably justify assigning all species in the *C. lineatus* group to the genus *Thalassiosira*. Several cultures of *Coscinodiscus radiatus* show extreme variation in valve morphology at small cell sizes. Similar valve variations were observed in *C. radiatus* grown on silicate-limited media.

A preliminary survey of bottle samples from the North Pacific has revealed a surprising number of centric diatoms with eccentric or linear valve patterns which do not fit any of the described species. (Booth, [Lewin])

The identification of small species of the diatom genus *Chaetoceros* is very difficult because few diagnostic characters are available; when resting spores are absent, the task is often impossible. By the use of the SEM as well as the light microscope, we hope to find characters of diagnostic value in differentiating these species. Studies of *C. septentrionale* Oestrup from four coastal sites in the North Pacific and North Atlantic yielded a much better description of the species than was previously available. Three types of girdle bands were found; their differentiation, as well as that of intercalary bands, is discussed for this and related species (Duke, Lewin, and Reimann, 1973). We are also investigating the fine structure of frustules of the species of *Chaetoceros* available in cultures. (Lewin)

#### B. Taxonomic Survey of Benthic Diatoms on an Intertidal Sandflat

A taxonomic survey of the benthic diatom flora of False Bay, an intertidal sandflat on San Juan Island, was undertaken during 1973. More than 50 diatom species were identified. Of these, about 10 species (4 centric species and 6 pennate species) are of major ecological importance since they constitute

the true epipsammic flora (those living attached to sand grains). One of the centric species was the predominant species at depth in the sediment. Its healthy pigmented cells were found down to a depth of 18 cm below the sediment surface in the outer part of False Bay. Physiological work will be undertaken with some of the ecologically important species. (Lewin; V. N. Raja Rao, Madras University, India)

#### C. Taxonomic Studies on Nereidae (Polychaeta)

A new family of errantiate polychaetes, the Notophycidae, was recently described by Knox and Cameron from New Zealand, with *Notophycus minutus* as its sole member. It was stated to be closest to the Hesionidae and also to show affinities with the pelagic Isopilidae and Pontodoridae. Another new genus and species, *Phyllodocella bodegae*, from central California was subsequently assigned to the family. It can be shown that both species are members of *Micronereis* Claparède (Nereidae) and that *Micronereis* is a true nereid. The description of the Notophycidae was based on a misinterpretation of several aberrant features of *Micronereis*. Therefore, *Notophycus* and *Phyllodocella* will be placed in synonymy with *Micronereis*. The latter, together with a genus to be named, will be moved into a new subfamily, which is considered as the most primitive group among the Nereidae. The new subfamily will require a modification of the diagnosis of the Nereidae. Besides the description of a new genus, additions to already known members of *Micronereis* will be made.

Investigations of another group of somewhat primitive Nereidae which all have bifid ventral parapodial cirri are under way. At least three representatives occur in the Northeast Pacific Ocean. As with the study of *Micronereis*, proper identification and classification of these species is not possible without consideration of the world fauna and generic revisions. A new subfamily will be proposed for these taxa. (Banse)

#### D. Benthic Polychaetous Annelids of British Columbia and Washington

Polychaetes account for 19, 34, and 64% of the average biomass in the three prevailing benthic communities of the continental shelf of Washington and obviously play an important role on the sea bed. To facilitate ecological work on the group, keys for the approximately 220 known species of the so-called errantiate polychaetes have been completed for the waters of British Columbia and Washington, incorporating also records from Oregon (Banse and Hobson, 1974). The treated area forms the central section of the Oregonian-Aleutian Biogeographic Province which extends from Point Conception, California into the Bering Sea. In respect to polychaetes, the section is the best known part of the province, yet a considerable number of taxonomic revisions had to be made and, disturbingly, many new records were found during the course of the study on the keys.

The work provides the first key for all genera of the entire cool-temperate North Pacific Ocean, and thus gives easier access to the specialized taxonomic literature anywhere in the area. The main body, the specific keys, give the diagnostic features in the conventional way, i.e., in a series of alternative choices. Additional characters are included, however, in order to prevent species not previously recorded from Washington or British Columbia from fitting the keys accidentally. The keys have already been used successfully in an adjoining area, San Francisco Bay. It is interesting to note that the fauna of the bay is better covered by this key than by the monumental "Key of the Errantiate Polychaetous Annelids from California" published by

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in 1968; evidently, the Atlas focuses on the biogeographic region south of Point Conception.

Work on the second and concluding volume is nearing completion. It will cover the other group of polychaetous annelids, the sedentariate forms, which comprise approximately as many species as the errantiate polychaetes in the area. The drafts are being tried out primarily on new collections deposited in the Provincial Museum in Victoria, British Columbia. (Banse; K. D. Hobson, Victoria, British Columbia)

#### *E. Taxonomic Studies of Planktonic Copepods*

Species of the copepod genus *Calanus* frequently dominate the marine zooplankton in boreal and arctic waters. Up to now there have been no operational means of identifying several species closely related to *Calanus finmarchicus*. Reanalysis of these taxa, using material from plankton samples collected throughout polar and boreal waters of the Northern Hemisphere, shows that there are three sibling species which have been previously combined under the names *C. finmarchicus* and *C. glacialis*. Several new taxonomic characters permit unequivocal identification of *C. finmarchicus*, *C. glacialis*, and a new species *C. marshallae*. Claims that *C. finmarchicus* and *C. glacialis* are subspecies are refuted; there is no evidence that the two species continuously intergrade either where they co-occur or where they are allopatric, nor is there evidence that the two species hybridize. *C. finmarchicus* is basically restricted to the North Atlantic Ocean and *C. marshallae* to the North Pacific Ocean and Bering Sea; *C. glacialis* is primarily an Arctic species, but its geographical distribution slightly overlaps those of the other two species. Taxa closely related to *C. finmarchicus* and *C. helgolandicus* probably represent two separate, but closely linked evolutionary lineages; species of these two lineages are placed in one of two species groups, the *finmarchicus* group and the *helgolandicus* group.

A taxonomic revision of the genus *Pseudocalanus* is in progress. (Frost)

#### *F. Barnacle Studies*

A major effort for several years has been devoted to a study of the barnacles of the *Balanus amphitrite* complex. This group is one of two groups mainly responsible for fouling of ships; it is even more noteworthy for fouling of coastal marine installations. Some members of the group have been and are still being used extensively in physiological studies. Therefore, it was important to establish the taxonomic status of the species assigned to the group.

A paper in press includes detailed descriptions of the 23 species in the *amphitrite* complex. Interspecific relationships have been evaluated descriptively, and statistically through the use of the generalized distance function and discriminant function analyses. The discriminant function has also been utilized as an aid in the identification of unknown specimens of a closely related pair of taxa.

Two other studies have been completed. The first on the eastern Pacific barnacles of the *B. tintinnabulum* complex, the other dominant group of ships' foulers, concerns four subspecies of *B. tintinnabulum*, all of which have been

accorded specific rank. Two other subspecies, previously thought to belong to an insular complex, are placed in synonymy. Three of the species are endemic in the eastern Pacific, whereas the fourth, with a wide range from Mexico to Peru, has been recorded for the first time as a member of the fauna of Brazil.

The second study is concerned with an intertidal barnacle of the genus *Tetraclita*, which has recently been revised by Ross, who raised three subgenera to generic rank and proposed new genera for two of the species. However, the status of the taxa remaining in *Tetraclita* was not dealt with by Ross. The only two representatives of the Tetraclitidae in the eastern Pacific belong to *Tetraclita s.str.*; one species is endemic and the other, which is widely distributed in the eastern Pacific, also has an extensive range in the western Atlantic. The other seven species of *Tetraclita* have an Indo-Pacific distribution. The paper will include a key and descriptions of the species, one of which has not been recorded since Darwin's (1854) original description. (Henry)

## XXIV. Marine Acoustics

This program has theoretical as well as applied aspects (see XXVI M). One goal is to understand the effects of environmental variables on the transmission of sound in the sea. Phenomena being investigated include the sound-scattering layers that are formed by organisms and migrate diurnally and the causes of migration as there are other layers which do not move; the effect of internal waves and microstructure in the propagation of sound waves; and the propagation of sound waves both in the water and in the sedimentary layers.

A program of field research, which is attempting to simultaneously study oceanic structure and acoustics has been started; it is directed toward understanding the mechanisms which give rise to fluctuations in acoustic signals. Past measurements of acoustic fluctuations have included only limited simultaneous measurements of index of refraction fluctuations in the transmission path. To develop an understanding of the observed acoustic amplitude and phase fluctuations from the properties of the medium, we need to know the space and time scales of the index of refraction. Acoustic fluctuations occur from scattering by the inhomogeneities in the medium caused by turbulence, layering, and other variations from the mean-sound-velocity profile. Transmission fluctuations which are a function of time can be associated with the slow horizontal advection of these random features across the acoustic path and the vertical oscillations of these features caused by internal gravity waves.

The present work will study the correlation between fluctuations at two separated acoustic towers with the fluctuations of environmental parameters as measured from three moored arrays and two self-propelled vehicles. The correlation between fluctuations along the two parallel acoustic paths should depend on the coherence of the internal wave field at approximately the same horizontal separation. By measuring the various horizontal and vertical coherences from both the moored and towed spectra, it is hoped that the present theories of internal wave behavior can be tested and used to predict the acoustic scattering. Thus we test both acoustic and internal wave theories with one experiment.

During 1973 we completed the analysis of our open-ocean acoustic-transmission fluctuation experiment, which is viewed by many as a landmark in the understanding of the relationship between acoustic transmission and oceanic structure. Sound was transmitted over a 17-kilometer horizontal path between two seamounts located 275 miles west of Grays Harbor, Washington. The fluctuations observed in the experiment exhibit distinct behavior which is tentatively explained as the result of internal tidal and wave motion in the ocean. The results are of sufficient quality to allow a more detailed comparison between theory and experiment than has been possible previously. In 1974 we started a program to carry out a new set of experiments on acoustic transmission and oceanic structure. Two experiments have been planned. The major one, designated MATE (Midway Acoustic Transmission Experiment), is scheduled for June 1976 (Figure 7); with the results, we hope to refine our models of the ocean's small-scale structure and processes. A preliminary experiment, designated PREMATE, will be conducted in the Georgia Straits in June 1975.

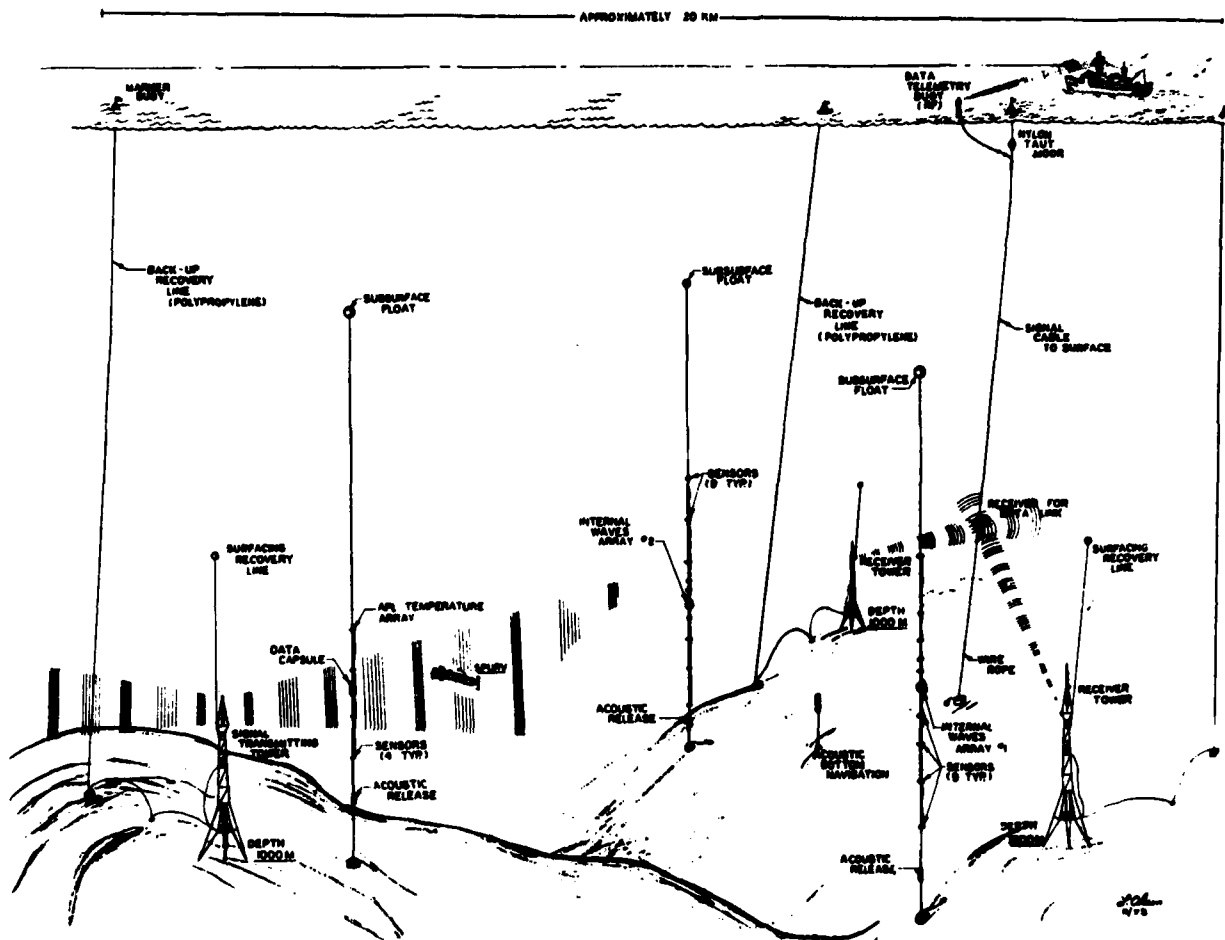


Figure 7. The Midway Acoustic Transmission Experiment (MATE) shown above combines several simultaneous but independent measurement programs.

MATE is essentially three experiments done simultaneously. First, acoustic-transmission fluctuations will be measured over a 15-20 km path in a broad range of frequencies. These fluctuations are theoretically related to the temporal and spatial variations of the oceanic parameters in the transmission path. By measuring the acoustic fluctuations and the oceanic parameters simultaneously we can confirm the validity of available theoretical models. Secondly, spatial scales of oceanic structure will be measured by our Self-Propelled Underwater Research Vehicle (SPURV); and, third, the temporal scales of oceanic parameters will be measured by moored instrument arrays. We intend to use three of the moored units which will be placed in the deep ocean to measure temperature, pressure, conductivity, and water velocity at a number of different depths and for durations up to one month. Hopefully, the data gathered from this extensive field program will allow us to describe the time variability of the ocean caused by internal waves and microstructure. This, in turn, should provide the basis for a better understanding of the ocean's acoustic propagation characteristics. (Ewart, Irish, Desaubies)

## XXV. Marine Resource Development

The purpose of this program element is to lay a firm scientific base upon which resources from the sea can be developed.

### *A. Methodology of Oil and Gas Resource Assessment*

The diverse methods being used to assess the undiscovered resources of oil and gas from sedimentary basins, which at best are only incompletely explored through drilling and at worst only indirectly explored through partial surface geological and geophysical techniques, lead to widely divergent results that attest to the inadequacies of existing methodology. Systematic and comprehensive investigations have begun into the relationships among geophysical parameters (particularly magnetic and gravity measurements and seismic velocities), geophysically derived basin volume, shape, depth characteristics, and facts and inferences about depositional regimens, geologic ages, lithologies, and diagenetic and thermal histories of basin-filling sedimentary rocks in an attempt to relate such relationships quantitatively to hydrocarbon productive potential. The objective of the research is to develop new and improved methods for assessing the potential resources of selected frontier and offshore depositional basins which will lead to estimates to which quantitative measures of reliability or confidence can be attached. (McCulloh)

### *B. Oil and Gas Resources of the Central Gulf of Alaska*

Geophysical data gathered jointly by personnel of the U. S. Geological Survey and the Department of Oceanography, under the technical direction of M. A. Holmes during a two-month cruise of 1974 in the central Gulf of Alaska, provide the starting point for a crude geological model of a structurally complex, composite depositional basin beneath the continental shelf. After suitable extrapolations from published studies of deformed Cenozoic strata onshore and from a few wells drilled onshore for oil and gas, inferences about occurrences in the subsurface offshore of hydrocarbon source and reservoir rocks will permit the model to serve as a basis for estimating a range of possibly recoverable oil and gas resources in the area. (McCulloh)

## XXVI. Applications of Oceanography

The purpose of this element is to provide the basic knowledge of oceanography and to adapt oceanographic tools for the solution of practical problems. Particular emphasis is placed on the development of predictive models of Puget Sound and adjacent waters for which it is necessary to first have a thorough knowledge of the oceanography of the area.

### *A. Atlas of Water Properties of Puget Sound*

This recently published atlas entitled "An Atlas of Physical and Chemical Properties of Puget Sound and its Approaches" is based upon observations made from 1952 through 1966. Vertical profiles of temperature, salinity, density as sigma-t, dissolved oxygen, oxygen saturation, and inorganic phosphate are included. The graphic presentation of the data should greatly simplify the use of the atlas for anyone making decisions based on physical and chemical properties of these waters. Ocean engineers, commercial fishermen, fish farmers, regulatory agency personnel, and legislators are among those who will be specially interested in this atlas. (Collias, Barnes, McGary)

### *B. Tide Measurements*

At the request of the Canadian Hydrographic Service, tide gauges were established at Port Angeles and Sekiu, Washington. The Port Angeles gauge was in operation from March through June 1973 and the Sekiu gauge from May 1973 to May 1975. These data were reduced monthly and submitted both to the Canadian Hydrographic Service and to the National Ocean Survey. (Collias)

### *C. Hood Canal Study*

A summary of the physical and chemical properties of the waters of Hood Canal, with particular emphasis on the waters near Bangor, was prepared at the request of the Trident Joint Venture Group. Data were then incorporated into a comprehensive environmental impact statement prepared by the U. S. Navy for the proposed construction of the Trident submarine base at Bangor. (Collias)

### *D. Skagit Bay Study*

A report on the circulation patterns and the temperature regime in northern Skagit Bay as related to the proposed siting of a nuclear power plant on Kiket Island was prepared for Seattle City Light and Snohomish Public Utility District No. 1. The summer surface-water temperatures in the main channels passing Kiket Island were among the lowest within Puget Sound; they averaged 11.7°C from June to August, or 2.5°C lower than found southward through Possession Sound. Principal contributing factors were vigorous tidal mixing, superimposed on a new northward flow of cold upwelled water from Saratoga Passage. Waters close to the shoreline away from strong currents were as much as 6°C warmer than those at midchannel. Maximum diurnal ranges at fixed locations approached 4°C and hourly changes occasionally exceeded 2°C. Since large changes in temperatures may occur rapidly and over short distances, the common concept of "near" and "far" fields as well as flushing models based upon uniform mixing are invalid for the Kiket Island area.

The temperature increase from cooling water from the proposed nuclear power plant would exceed only slightly the average hourly variability and would be difficult to detect against the natural background if discharged through a suitable diffuser at a favorable midchannel location. It was concluded that "the proposed site at Kiket Island appears to be one of the most favorable within Puget Sound proper for dispersing added heat and managing its effect upon ambient waters." (Collias, Barnes, Lincoln)

#### *E. Ecological Studies of Red Algae*

In recent years, the growing interest in utilizing the resources of Pacific Northwest coastal waters has led to the investigation of several algal species as possible new resources for commercial exploitation. Investigations in both the State of Washington and British Columbia have been centered on the large foliose, subtidal red alga, *Iridaea cordata* (Turner) Bory, and other species of the order Gigartinales which are a source of carrageenan, a high-quality emulsifier and stabilizer used in numerous industrial and food products.

The aim of this study was to determine the environmental factors that influence the growth and distribution of *I. cordata* and the community in which it is found. Competition with kelps was found to set the lower limit of the population at or below -1.0 m. At the upper limit of the *Iridaea* beds the species is subject to loss of weight and possible destruction after two or more hours of emersion in a bright sun. The species establishes itself on granite or limestone substrates but apparently not on coarse-grained sandstones. The smallest-sized particle on which blades were found growing was 35 mm in diameter. The occurrence of *I. cordata* in large beds was correlated with maximum tidal current velocities between 0.06 and 0.38 m/sec. The algal communities associated with *I. cordata* in winter differed from those, in summer. (Hruby [Lewin])

#### *F. A Collection of Marine Algae Cultures*

A large collection of cultures of marine algae (both planktonic and benthic forms) is maintained in the Department of Oceanography; considerable attention is devoted to the isolation of new cultures for the collection. The cultures are used both within the Department and elsewhere within the University; also, subcultures of many species are requested by other universities, government agencies, and private industry. With the growth of various aquaculture enterprises, there has been an increased demand for certain algal species to serve as food sources for larval and adult stages of various marine invertebrates. (Lewin)

#### *G. Production of Useful Polymers from Marine Algal Cultures*

Mass cultures of various microscopic algae (diatoms and small filamentous red algae) were grown and the cells harvested in the Department of Oceanography for chemical studies by Forest Resources, University of Washington, and the Department of Chemistry, University of Puget Sound. The aims are to characterize the types of polymers produced by marine algae and to select species with high yields of polymeric material. Industries concerned with extraction of polymers from dried seaweeds are interested in the potential use of local algal species for extraction of useful polymers. These studies were undertaken with Sea Grant support. (Lewin)

## *H. Effects of Man-Made Chemical Perturbations*

The objectives of these studies are 1) to develop a sufficiently sophisticated understanding of marine ecosystems under man-made perturbations to permit predictions of short- and long-term responses of the primary productivity and fish population within a specific coastal area to high pollution inputs, 2) to assist governmental agencies in establishing effective water-quality standards, 3) to assess biological response of marine ecosystems subjected to man-made perturbations. Eutrophic systems (Puget Sound, Southern California Bight, and the northwest coast of Africa upwelling zones) and oligotrophic systems (Eastern Mediterranean) are being examined for comparison of the impact of nutrient and toxic compound addition. These studies include determining toxicity thresholds, uptake kinetics, correlations with water-mass transport indicators, random pulsing, and predictions of dispersion and integrated transport within the ecosystem. (Pavlou)

### *I. Pathways and Retention Times of Pollutants*

The objective in this project has been to develop techniques for predicting pathways and retention times of pollutants introduced into fjords, with emphasis on the deep basins of Puget Sound. As a first step in achieving this objective, we have developed an approximate description of near-surface circulation in fjord segments, using similarity techniques (see VI A).

A second phase of the project is to investigate probable distribution and dispersion of water-borne pollutants that may be discharged at specific locations and to define qualitatively, at least, the general circulation within certain inlets in Puget Sound. Experiments are carried out under different types of tidal conditions corresponding to specific times. In addition, in those locations where river discharge has a significant effect on circulation or pollutant dispersion, the effect of run-off is evaluated for conditions of high, mean, and low discharge rates.

Dispersion studies involve injection of a dye of known concentration and relative density at a rate scaled to a specific pollutant discharge. Dye transport and dispersion is recorded photographically both by single-frame photographs at appropriate intervals and by motion pictures, thereby providing a suitable means of evaluating the dye motion and dispersion and a permanent graphic record. Overall surface circulation within each fjord subregion is being investigated by means of a powder on the surface.

The effectiveness of this technique in showing the circulation characteristics over the entire study area at any one time is shown by experiments with the Puget Sound hydraulic model. Past investigations with the Puget Sound model have demonstrated that tidal currents, circulation, and water exchange as observed in the model are generally representative of the prototype and will provide a reliable means of investigating these dynamic characteristics within a relatively short time. Further, these studies provide a valuable guide for the most efficient conduct of field studies and/or monitoring activities that subsequently may be indicated. The hydraulic model is an especially useful tool in this connection inasmuch as the dynamic behavior of Puget Sound is extremely complex and an adequate understanding is often very difficult to obtain by field observations alone without intensive and costly effort. (Pearson [Winter, Lam, Lincoln])

### *J. Waste Disposal in Puget Sound*

At the request of the Washington State Department of Ecology, a study of two potential locations for sewer outfalls was made. One site was at the north end of Pickering Passage and the other off Union in southern Hood Canal. Three field trips were made to the study areas to determine the chemical and physical properties of the waters. These data plus existing data will be used in the preparation of a report discussing the potential effects of the proposed sewer outfalls upon the local areas. This project is part of the Division of Marine Resources programs. (Loehr [Collias, Duxbury])

### *K. West Point Outlet Study*

As a followup of our successful field experiments at Kiket Island in 1971 (which were part of a significant Puget Sound environmental impact study), we have begun a new cooperative program, involving similar measurements, that is related to impact studies for METRO. In this work we are tagging the outfall at West Point with dye and mapping the temporal and spatial distribution of the effluent as it diffuses into Puget Sound. (Bendiner [Ewart])

### *L. Interrelationships among Chemical, Physical, and Biological Parameters in the Puget Sound Main Basin*

The aims of this study are: 1) to identify and quantify the sources of the nutrients, 2) to determine the budget of nutrients in the main basin of Puget Sound, especially in the vicinity of the four major METRO sewage outfalls, Alki Point, West Point, Carkeek Park, and Richmond Beach, and 3) to provide a comparison of present-day conditions of nutrient concentrations and plankton off West Point with conditions in the mid-1960's.

Major exchanges of matter, such as nutrients and other salts, and fluxes of these properties involve the salt water sources, river and sewer discharges, biological activity, and direct precipitation. The emphasis will be to quantify these processes to determine the long-term effects of METRO's sewage outfalls on the main basin of Puget Sound. A major effort will be placed upon the interaction of nutrients and other factors with the biota.

Cruises at three-week intervals began in November 1974 and will continue through November 1975. Approximately 25 stations throughout the main basin are to be occupied during each cruise to detect local changes and to evaluate the fluxes of chemical constituents as a result of physical and biological processes. Circulation patterns determined from drogue measurements will be compared with measurements made with the hydraulic model of Puget Sound at the Department of Oceanography. Short-term variability of water characteristics over several 39-hour periods will be measured near the West Point sewage outfall during both neap and spring tide-conditions. Uptake of  $^{15}\text{N}$  labeled compounds will be measured on a quarterly basis to estimate utilization rates of the various forms of nitrogen by phytoplankton.

The information collected in the mid-1960's showed that the open water off Seattle was largely unaffected by pollution providing nutrient salts. Since then the sewage outfall at West Point near one of the principal stations has been in full-scale operation.

Two blocks of data will be collected at the previously occupied location (off West Point) during two time periods: (a) May or June when river run-off is high and very large phytoplankton blooms occur and (b) late summer or early autumn when run-off is low. The latter period represents the greatest gap in our knowledge concerning the interpretation of seasonal events in phytoplankton dynamics of the central basin of Puget Sound; earlier studies did not sample often enough to elucidate the dominant processes controlling phytoplankton growth. The low-run-off period may also be expected to be critical in the interpretation of the effect of nutrient additions to this area of Puget Sound. During each period, daily sampling will be carried out for 3 weeks, beginning several days before the spring tide (when turbulence from tidal energy may be expected to be at a maximum), through the neap tide (when stability of the water column becomes favorable for phytoplankton development), and continuing to the end of the ensuing spring tide. In this manner, analyses of these data will not only help to elucidate the development and dissipation of phytoplankton blooms and the role of the various physical and chemical processes which govern the timing as well as the level of production but will also indicate differences, if any, in conditions since the mid-1960's. (Anderson, Richards, Collias, Whitledge)

#### *M. Quantitative Acoustic Estimation of Zooplankton Concentration*

This research was undertaken to develop, and demonstrate the use of, a quantitative acoustic method of assessing the standing stock of zooplanktonic sound-scattering organisms. Acoustic theory predicted such methods, and some attempts had been made to use them for estimating the abundance of sound-scattering organisms in the Deep Scattering Layer. Theory also described the relationship of size and composition of organisms to the target strength which, combined with recent measurements of target strength, allowed prediction of target strength for the species (*Euphausia pacifica*), used in this study. A method was developed to determine a single estimator of target strength which represented the entire size range of the target population. Acoustic theory relates that a measure of the returning signal strength from an insonified volume divided by the target strength of an individual scatterer gives the number of scatterers in that volume.

A field sampling study was carried out for one year in Port Susan, northern Puget Sound to determine the time and space distribution of a population of euphausiids on a scale previously impossible to achieve. In order to provide an independent estimate of standing stock for comparison with the acoustic estimates, samples were taken with vertically and horizontally towed nets. The vertical net was designed to fish downward because a preliminary study had shown that euphausiids were caught in significantly higher numbers when a net is fished downward than when it is fished upward. Both nets were electrically operated and had depth telemetry. The preliminary results of the field study indicate that the acoustic method is at least as accurate at estimating standing stock as net samples and, in addition, permits rapid assessment of the spatial distribution of sound-scattering organisms.

Investigations are continuing into the persistence of the time and space distribution of the population, seasonal variability, and some aspects of the scales of patchiness in the horizontal and vertical planes. The evaluation of the acoustic equipment also continues so that criteria for future systems can be determined. (Macaulay [English])

### *N. Ecological Baseline and Monitoring Study in Port Gardner*

This study grew out of mutual interests and concerns about potential future changes in the marine ecosystem of Port Gardner, northern Puget Sound and adjacent waters. Individuals and groups in the state and federal governments, the university, and industry repeatedly expressed interest in the possible magnitude and value of benefits to populations of marine organisms which could arise from pollution control enforcement actions. The purpose of our current studies is to describe the marine environment and the populations of organisms in the study area before proposed pollution control installations and waste load reductions decrease the concentrations of sulfite waste liquor (SWL) from pulp mills; and thereafter to conduct a monitoring program adequate to detect significant related changes in the ecosystem so that the magnitude of the resultant benefits of waste treatment can be evaluated. With the Environmental Protection Agency (EPA) and the State Department of Ecology, we have jointly established a study coordinating council to review and define current investigations by the participating agencies.

On twelve monthly hydrographic cruises, conducted from May 1973 through June 1974, chemical water-quality observations were made to provide a background of standard hydrographic parameters and of concentrations of SWL against which biological changes can be assessed. Dissolved oxygen and the inorganic nutrient ions of phosphate, silicate, nitrate, nitrite, and ammonia were also sampled on most cruises. During the future monitoring program, the periods between hydrographic cruises will be lengthened. Efforts will be made to develop an acceptable computation procedure to estimate total SWL in a volume representative of Port Gardner.

Quantitative data on bottom invertebrates collected in the same period have been correlated with distance from the mills' diffuser; the results demonstrate an increasing abundance of invertebrates along depth contours south of the deep water diffuser outfall. The significance of this information will not be known until it can be compared with data collected after waste water treatment controls have been accomplished. Another intensive sampling survey will be conducted in the mile southward from the deep water diffuser outfall to examine the relationships between distribution and abundance of benthic invertebrates and the statistical interactions of depth and distance from the outfall.

Additionally, a monthly sonic survey with a high frequency (105 kHz) echosounder was made for one year to assess the distributions and abundance of fishes and zooplankton concentrations acting as acoustic targets. Midwater nets were used at selected locations and depths to sample the concentrations of zooplankton forming widespread mid-depth sound-scattering layers. The most important result has been the identification of a water volume at intermediate depth devoid of sonic targets. These targets can be found, however, at corresponding depths in other areas of Port Gardner and Puget Sound. The location of the void appears to correspond to high SWL concentrations in the plume from the deep water diffuser outfall shared by the Scott and Weyerhaeuser pulp mills. In the future, more intensive efforts will be made to determine the extent, periodicity, and other properties of the void. Observations of the sonic void, chemical water-quality, and oyster larval bioassays (the latter to be done by the Department of Ecology) will be correlated.

A series of monthly hauls at several depths with the research beam trawl is being made to describe present populations and to detect major changes of specific composition and abundance in fishes, shrimps, and crabs at Port Gardner and at two control stations. Duplicate hauls at depths of 5, 10, 20, 30, 40, 60, and 80 m are being made at all stations; 120 m is being sampled at two stations, and 150 m at one (Port Gardner). In 1975, Port Gardner will be sampled monthly and the control stations, bimonthly.

An initial beach survey southward from the Weyerhaeuser mill site to Mukilteo was made in 1973 to describe distributions and abundance of present populations of plants and animals so that gross changes corresponding to reductions in pulp mill effluents could be detected. This should be followed by an annual resurvey of the Port Gardner beach to document any major changes in plant and animal populations.

The Department of Ecology has investigated the distribution of juveniles of two salmon species and performed live box studies with these animals. The Department of Ecology has also made growth phase studies and bioassays using oyster embryos which will not be described here.

In conclusion, the first year of the study was primarily devoted to an intensive effort to obtain the most baseline observations possible within limitations of manpower and funding. We now have the observational data to serve as a beginning of an adequate environmental and biological baseline of Port Gardner. Data reduction and analysis can now be given more attention while further baseline observations continue to be made in the second year of the study. (English and co-workers)

#### *O. Oil Baseline Study in Puget Sound Offshore Habitats*

In the framework of the Oil Baseline Study of the Washington State Department of Ecology, we are studying the so-called offshore habitats, through the depth range of 5 to 20 m. We will sample at 2-month intervals for one year at Cherry Point and Guemes Channel near the refinery docks, both considered to be high risk areas, and at East Sound (Orcas Island) for the control area.

Four bottom contours, 5, 10, 15, and 20 m, referenced at MLLW, are sampled for bottom sediments and invertebrates with the van Veen grab and for fishes, shrimps, and crabs with the research beam trawl. Hydrographic samples, including oxygen, five nutrient salts, sulfide waste liquor, and chlorophyll, are taken at 0, 5, 10, 15 and 20 m. In addition, macroplankton and micronekton are sampled with a midwater trawl; zooplankton, fish eggs, and larvae by vertical net tows, and organisms near the surface with a neuston net. Acoustic targets are observed in the water column with an echo-sounder. Two of the projected six cruises have been completed. (English and co-workers)

#### *P. Investigation of the Hydraulic Regime and Physical Nature of Bottom Sedimentation in the Columbia River Dump Site*

From an oceanographic point of view the region just seaward of the mouth of the Columbia River is extremely complex. At any given time the flow in this region depends upon the relative magnitudes of the tides, river run-off, wind-driven coastal current, and wind waves. The situation is further complicated by the geometry of the river mouth and bar. Therefore, one must focus upon a

particular facet of this complicated region if real progress is to be made in elucidating sediment transport phenomena. The present investigation is designed to determine the fate of dredge spoils and can be divided into examination of those processes acting while the material is being dumped, and those phenomena responsible for moving the material once it reaches the bottom. Disposal is usually accomplished in fair weather, whereas the latter phenomena are associated with extreme events such as winter storms or periods of significant wave activity. Our approach makes use of these considerations by concentrating on the flow near the sea bed over the region of general interest. Measurements throughout the water column are proposed only in the vicinity of the dump site and river mouth and only during periods of maximum and minimum river run-off. In this manner, use of available oceanographic tools can be maximized and information of the type desired can be obtained from an oceanic system too complicated to be completely elucidated at reasonable cost. This research program will involve two major thrusts: a relatively complete sampling and analysis program for bottom sediments and a study of the hydraulic regime at the dump site. (Sternberg, Creager, Smith; J. Whetten, Department of Geology)

#### *Q. Computer Applications*

A sophisticated shipboard computer facility has been developed to meet the requirements of investigators of the dynamic phenomena in marine ecosystems. The Interactive Real-time Information System (IRIS) provides a facility at sea for real-time data acquisition, for batch mode simulation modeling, and for interactive programming by shipboard scientists in a time-shared mode. The facility allows all investigators to interact with the data base acquired during the cruises and to design experiments in a highly adaptive manner. Ashore, the IRIS facility is a central computer center available to all program investigators for processing their data.

The computer system is a heavily graphics-oriented, dual-processor DED PDP 11/45 with large core and disk memories and most major peripherals. The system is van-mounted for use on ships of opportunity. (Kelley)

